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TOWARDS AN UNDERSTANDING
OF
THE URBAN HEAT ISLAND IN THE DETROIT-WINDSOR AREA

BY
IMAIYAVALLI KUMANAN

A Thesis
Submitted to the Faculty of Graduate Studies through the
Department of Geography in Partial Fullfillment
of the Requirements for the Degree of
Master of Arts at University
of Windsor

Windsor, Ontario

1970

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ABSTRACT

The variability and the magnitude of the urban heat island in the Detroit-Windsor area is analysed temporally. The influence of certain climatic elements on the urban heat island is also investigated.

The urban heat island has been studied by analyzing the temperature differences between an urban and two rural locations on a three-hourly basis for a period of ten years. The Detroit City airport is considered to represent the urban location while the Wayne County Metropolitan airport and the Windsor airport are considered to represent two rural locations. The city-country temperature differences are statistically tested for significance using paired t-test. This is done on an yearly and monthly basis for each observation hour and for the whole day.

The dependence of the city-country temperature difference on temperature, wind speed, humidity and sky cover has been investigated using the multiple regression analysis technique. This has been done for a winter month and a summer month for each city-country combination.

The temperature difference has been found to be statistically significant during most hours of the day for City-Windsor, and only during the night, early morning and late evening hours for City-Metro. During the afternoon hours significance is found only in a few cases in the City-Metro

difference.

When seasonal variation is considered, the difference is found to have a maximum in fall and a minimum in winter. The heat island is also found to vary in magnitude through the day. The differences reach a maximum late in the night and have a minimum in the afternoon. However, the drop in the City-Windsor difference is small, with the difference remaining high even in the afternoon. On the contrary the City-Metro difference exhibits an almost complete dissipation of the heat island and a possible formation of a cold island in the afternoon of some months.

Cloudiness and wind speed are the important climatic elements which influence the temperature difference particularly at night. The actual temperature has a significant effect in summer. The vapour pressure has negligible effect.

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CHAPTER I

INTRODUCTION

Today scientists of various disciplines who deal with the ecology of man are interested in the study of the urban atmosphere. The urban atmosphere is the result not only of the general climate of the area and of the modifying influences of the local relief, but also of man's attempt to create a suitable place in which to live. This has resulted in the modification of the conditions in the boundary layer. Changes have occurred in vertical and horizontal movement of air, radiation, temperature, pollution and rainfall in the urban areas. Measurement of these factors are difficult due to the complexity of the urban surfaces. It is also difficult to isolate the urban influences per se from other local controls that would exist even if the town were not there.

In spite of the complexities involved in the study of the urban climatology, certain elements have received some attention. With the routine measurement of temperature the urban heat island has been observed though in a crude manner. The studies at the beginning were mostly descriptive and few in number. No attempt was made to quantify or to study the processes influencing the formation of the urban heat island. Some studies show the seasonal variation in the inten-

sity of the urban heat island. More recently, moving observation techniques have been employed in Europe, North America and Japan where heat islands have been observed in varied types of locations in small and large cities. Few studies have been undertaken to show the influence of certain factors on the urban heat island. Very little is known about radiation, winds and evaporation rates in urban areas, a knowledge of which is essential to an understanding of the processes involved in the formation and dissipation of the urban heat island.

The present study attempts to analyze the city-country temperature difference on a three-hourly basis in the Detroit-Windsor area for a period of ten years. Data for two rural and one urban location are used in the study. Statistical analysis is done to test the significance of the differences. In an attempt to study the influence of certain factors on temperature difference, a multiple regression analysis is done for a winter and a summer month. For the two months, three-hourly temperature differences between city and country locations were related empirically with wind speeds, cloud amounts, temperatures and vapour pressures.

Since the present study is based on three-hourly temperatures, it shows not only the variability of the heat island intensity through the seasons, but also the magnitude of the heat island variability throughout the day. On the contrary, previous studies in other areas using maximum, minimum or mean temperatures show only the general heat island

conditions. A detailed study has not been attempted in this area before, with the two cities being considered as one urban entity.

CHAPTER II

THEORY AND REVIEW OF LITERATURE

1. Theory

According to leading urban climatologists, Kratzer¹, Landsberg² and others^{3,4}, the factors that have been isolated as contributing to the temperature difference between city and countryside include:

1. The physical properties of the construction materials of the city. The surface of the city most of which is made up of concrete and brick, has a much higher conductive capacity and therefore possesses a greater ability to absorb and store daytime solar radiation. In contrast to the urban surfaces, the countryside absorbs less heat. Takeshi Kawamura⁵ in his study of Kumagaya states that the construction materials of the city play an important role in deciding the city temperature. On the other hand, Davis³ found only very small rural-urban difference in conductive capacity between Fort Wayne, Indiana and the surrounding countryside.

2. The unevenness of the city surface. Structures of different sizes and shapes projecting into the sky compared to the even surface of the countryside result in the effective surface area of the city being much larger than that of the rural countryside of equivalent size. In the city, the entire

city surface is used to absorb the solar energy, whereas in the countryside the heat is stored only in the surface vegetation. The uneven surface of the city also has a braking effect on the wind reducing the wind velocity, thereby lowering the convectional heat loss which results in a city- country temperature difference.

3. The artificial generation of heat in the urban areas. This is an important factor in the higher latitudes in the winter and in large industrial cities. Heat is produced not only by factories but also by cars and humans. Garnett and Bach⁶ estimated that for the city of Sheffield, England, the artificial radiation heat represented nearly a third of the net radiation balance.

4. The urban water balance which is different from that of the rural countryside. Precipitation that falls in the city does not get disposed of in a natural way. Rain-water is removed immediately by sewers. Snow is removed mechanically or by the addition of salt. In contrast to this, in the countryside much of the precipitation remains in the uppermost layers of the soil. This results in the actual evapotranspiration in the countryside remaining close to the potential evapotranspiration rates. The heat energy used in evapotranspiration in the countryside results in the lowering of temperatures. In the city, since most of the precipitation is removed, less energy is used for evapotranspiration. This heat energy instead, is used to heat the air in the city resulting in increased temperatures. Since no studies have been done on

the urban-rural evapotranspiration, it is not possible to estimate the increase in temperature due to this factor alone.

5. The urban ~~haze dome~~ caused by air pollution. The air in the city is polluted due to the solid, liquid and gaseous contaminants released from factory wastes, incinerators and automobiles. This may vary depending on the functional character of the city. A heavily industrialized city will vary in its pollution content from that of a small town.

The suspended solid particles in the air reflect sunlight, thereby affecting the incoming shortwave radiation as well as the outgoing radiation. Emslie⁷ found that Scarborough, a suburb of Toronto received 4.6% on the average and 6.6% on Wednesdays more solar radiation than at Bloor street, Toronto. Conrad East⁸, comparing city-country locations in Montreal found that Montreal received 91% of the total received at Sainte Therese. He also found that attenuation was greater under cloudy skies than with clear skies, and that the urban effect was at a maximum during the winter months. Sekiguti⁹ noted that strong insolation was measured in the residential areas, while weak insolation was recorded in the industrial areas under stable conditions in Tokyo. When wind velocity was higher, the regional difference in insolation was small.

6. The height of the active surface of the city. The active surface of the city is much higher than that of the countryside and depends on the height of buildings. At night this results in cooler air at the rooftop level, while

in between the buildings the air is still warm and is trapped giving the city a higher temperature than the countryside especially in the early morning hours.

2. Review of Literature

Though early scientists were aware of the temperature difference between cities and countrysides, the first quantitative analysis was done by Luke Howard¹⁰. As early as 1809, he observed a temperature difference between the city of London and its surrounding countryside. Based on data from 1807-1816, he found a maximum difference of 2.2°F during the fall months and a minimum difference of $.5^{\circ}\text{F}$ during the spring months. Although his thermometers were exposed at different heights and were far from being standard, his work was very extensive and is referred to by many authors.

An excellent study by Kratzer¹ in 1937 dealt with all aspects of city climate. His work, unlike that of Howard was an effort to bring together the works of others into one volume, and is very comprehensive. He refers to daily variation of temperature difference at two-hourly intervals for Bremen in 1931/32, Dresden in 1932/33 and Jena for the summer of 1945. The temperature difference was found to vary from a low of $-.2^{\circ}\text{C}$ in the afternoon to 1.4°C during the mid-night hour in Bremen, whereas in Dresden the difference varied from -1.6°C to 3.0°C . There is no evidence that a statistical method was used to determine the significance of these differences.

A more recent study is that of Chandler¹⁰ on the city of London. He, like the two authors before him, dealt with all aspects of the city climate. His studies were based on a long period of data and showed the use of statistical methods in analyzing the city-country temperature differences, but he used only mean, maximum and minimum temperatures in his study. He referred to a two-hourly comparison based on one week's data which showed maximum differences in the early morning hours and minimum differences in the mid-afternoon.

Nakamura¹¹ in his study of the city temperature of Nairobi (population 267,000), an equatorial city, found a temperature difference of 1.3°C in the minimum temperatures, but no conspicuous difference in the maximum temperatures. Very few studies have been done in the low latitudes.

The urban heat island has been studied not only by analyzing the published meteorological data, but also by using the moving observation technique. Automobile traverses for three California cities by Duckworth and Sandberg¹² showed a difference of 20°F between the densely built-up business districts of San Francisco and the surrounding area on a clear, calm night. They were of the opinion that the most important single factor causing this difference was the physical structure of the city.

Oke and Hannell¹³ found a temperature difference of 16.2°F for Hamilton, Ontario with a population of 300,000 by the moving observation technique. They were able to identify two separate cells to the urban heat island, one in the

industrial and the other in the business sector. In their opinion, the former cell which was the dominant one was caused by large amounts of heat generated by the steel industries and by counter-radiation from the pollution haze.

Mitchell¹⁴ found that at New Haven, Connecticut a mean temperature difference of 1.0°F was shown for the city-airport values for the winter season. The mean difference was 1.1°F on week days and $.5^{\circ}\text{F}$ on Sundays. He attributed this to less heat and pollution on Sundays than on week days. He was of the opinion that the higher city temperature was caused by the city itself.

Duckworth and Sandberg¹² showed that the urban differential increased with city size, but at a relatively slow rate. They found differences of $4-6^{\circ}\text{F}$ for Palo Alto, $7-9^{\circ}\text{F}$ for San Jose and $10-12^{\circ}\text{F}$ for San Francisco with populations of 33,000, 101,000 and 784,000 respectively. Landsberg² presented a table showing the excess of mean annual city temperature over that of country by size of cities. Cities over one million population had a mean temperature excess of 1.3°F , while the corresponding figure for cities with a population of 500,000 to 1 million was 1.1°F and for cities between 100,000 and 500,000 it was 1.0°F .

Generally there is a lack of studies regarding the processes controlling the urban-rural temperature difference, mainly due to the complexities of the urban areas. Fuggle and Oke¹⁵ outlined a scheme for studying the effect of

long wave radiation on the intensity of the heat island in Montreal. Fuggle¹⁶ had done an analysis on an hourly basis for Montreal as part of the study on the long wave radiative flux divergence and the urban heat island of Montreal. The analysis done initially for January and April, 1968 indicated a lower temperature in the city in 30% of the observations.

The influence of certain climatic elements on the city-country temperature difference was studied by Sundborg² in Uppsala, Sweden. He used an empirical expression relating the temperature difference to sky cover, wind speed, temperature and vapour pressure, and determined the coefficients by multiple regression analysis. Duckworth and Sandberg¹² used Sundborg's formula in the San Francisco area and found that their surveys substantiated the general direction of this relationship with a few exceptions. Chandler¹⁰ included the temperature range as an independent variable but omitted the vapour pressure on the grounds that it had negligible effect on the temperature difference. Kawamura⁵ used the cloud amount of the preceding daytime and found a similar relationship for Kumagaya. In all these studies, the cloud cover and wind speed were found to have greater effect on the temperature difference than the other variables.

In general the literature survey shows a lack of statistical techniques used. Significance tests were not used to detect any significant temperature difference. There is a general lack of studies based on long term records showing the

variation through the day.

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CHAPTER III

METHODOLOGY

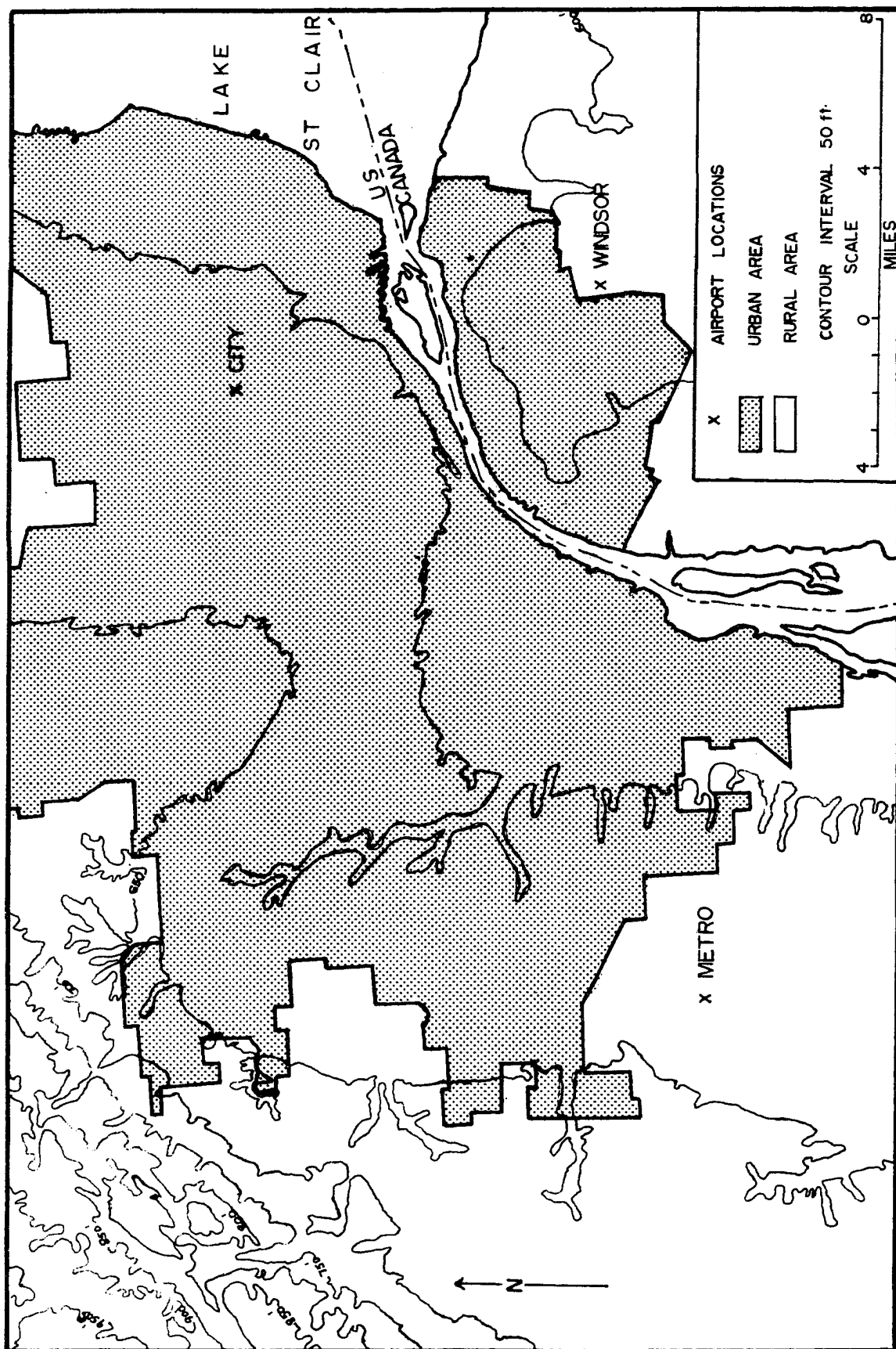
1. Site of the Study

The cities of Detroit and Windsor (42°N , 83°W), including the nearby built-up areas, occupy an area of about twenty miles in radius and lie at the western end of Lake Erie (Fig. 1). The Detroit river and Lake St. Clair divide the two cities.

Except for the Irish hills at an elevation of 1000-1250 feet forty miles north-west of the city of Detroit, the land is relatively level at an elevation of about 600 feet. On the Canadian side, the land is almost flat. Lake St. Clair, bordering the north-eastern section of the city and covering an area of about 400 square miles, is shallow and is frozen during the winter¹.

The Detroit-Windsor urban complex is mainly industrial and specializes in the automobile industry. It has a population of approximately $4\frac{1}{2}$ million². For purposes of this study, the city of Detroit and the city of Windsor are considered to be one single urban unit. Previous studies undertaken in this area show that only one side of the political boundary is considered as in the case of the study of the airport and city temperatures by Clarence J. Root³, which

FIG. 1 MAP OF DETROIT AND WINDSOR



was done only for the city of Detroit. Since Windsor is a part of the Detroit urban area, divided only by the political boundary, it is essential that both cities be considered as one entity, for any meaningful study of the area.

The three stations used in the study, the Detroit City airport, Wayne County Metropolitan airport and the Windsor International airport provide an urban location and two rural locations. In the following sections, the Detroit City airport will be referred to as 'City', Wayne County Metropolitan airport as 'Metro' and the Windsor International airport as 'Windsor'. These three stations were the only three available with a long period of temperature records and of necessity are considered satisfactory for the purpose of this study. The City airport in the north-east core of the city is considered to be representative of the urban area, while Metro airport in the south-west edge of the city in a semi-rural setting and the Windsor airport in the south-east edge of the city in a relatively open area are considered the two country locations.

2. Instrument Location

For any comparisons to be made between these locations, it is necessary that the instruments used to measure temperatures have standard ground exposures. Another important consideration is that the instruments have remained at the same site throughout the period of study i.e. from 1960 to 1969. It is found that except for the Windsor location, in the case of

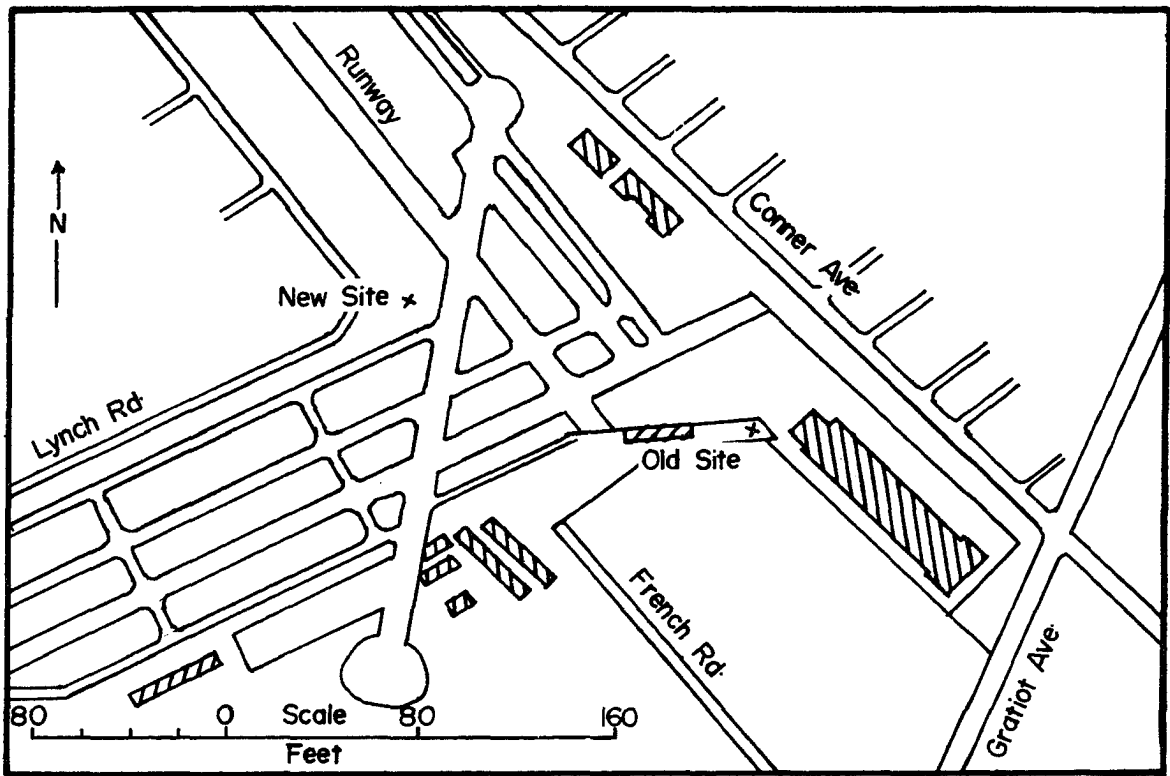


FIG. 2 CITY AIRPORT INSTRUMENT SITE.

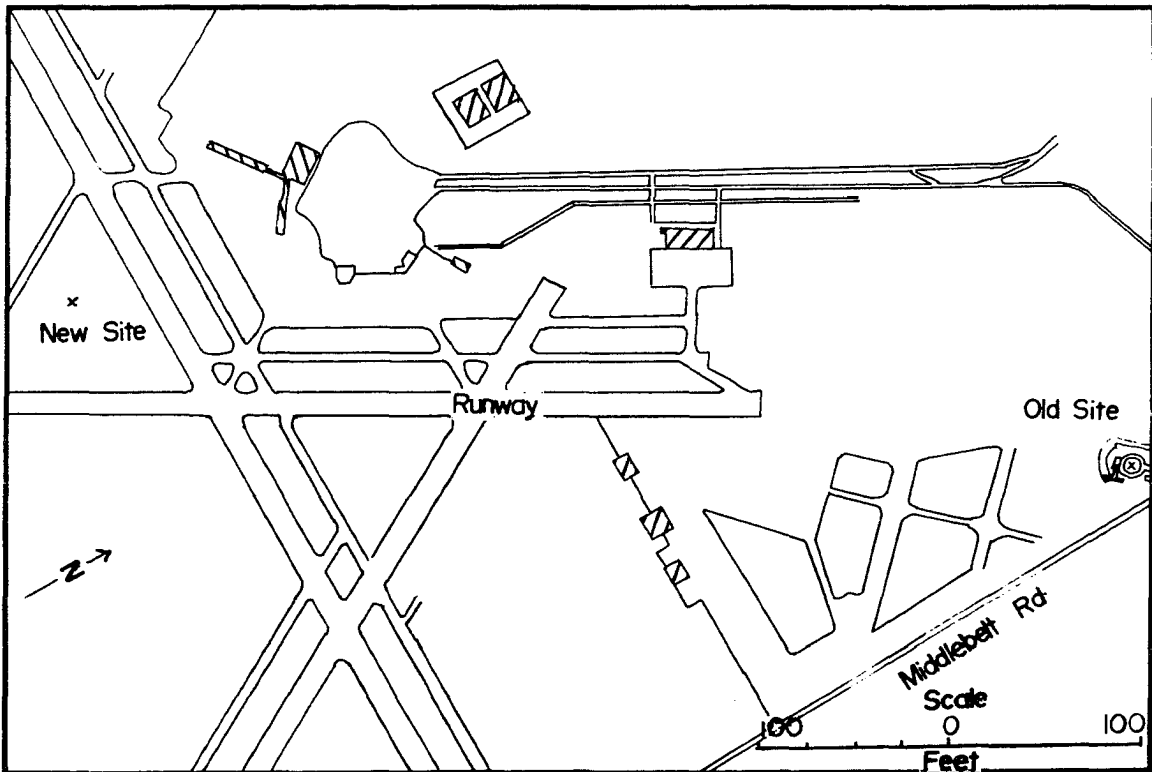
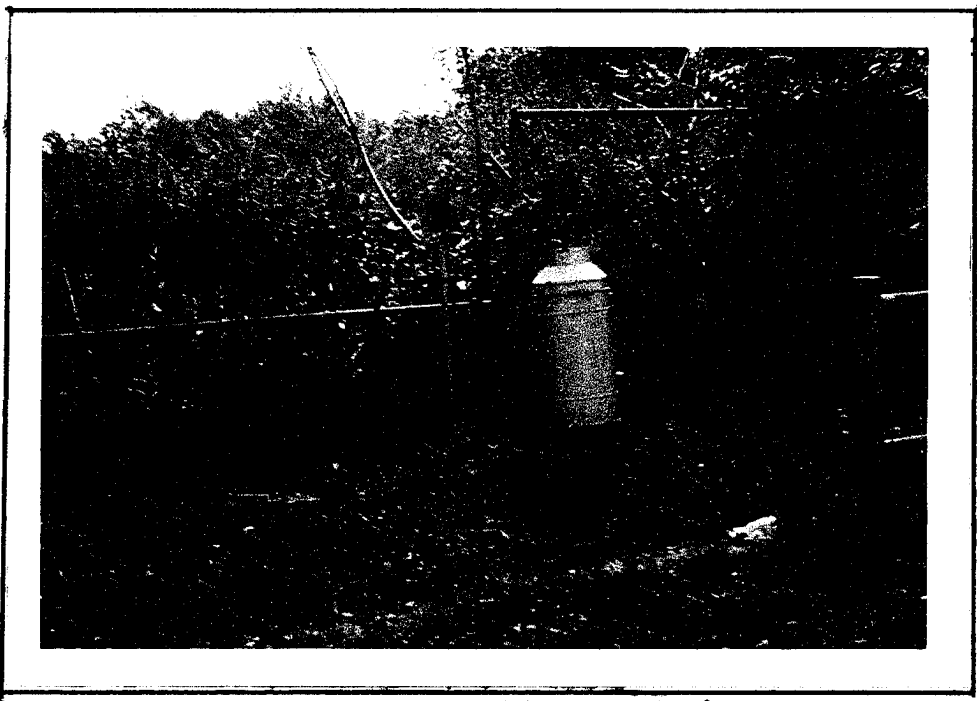
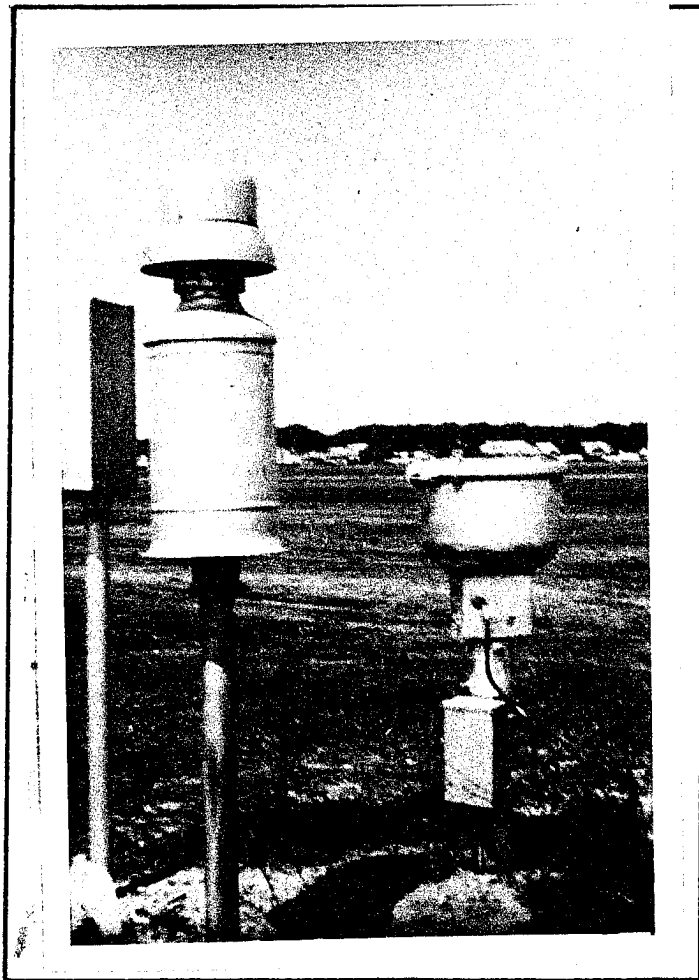


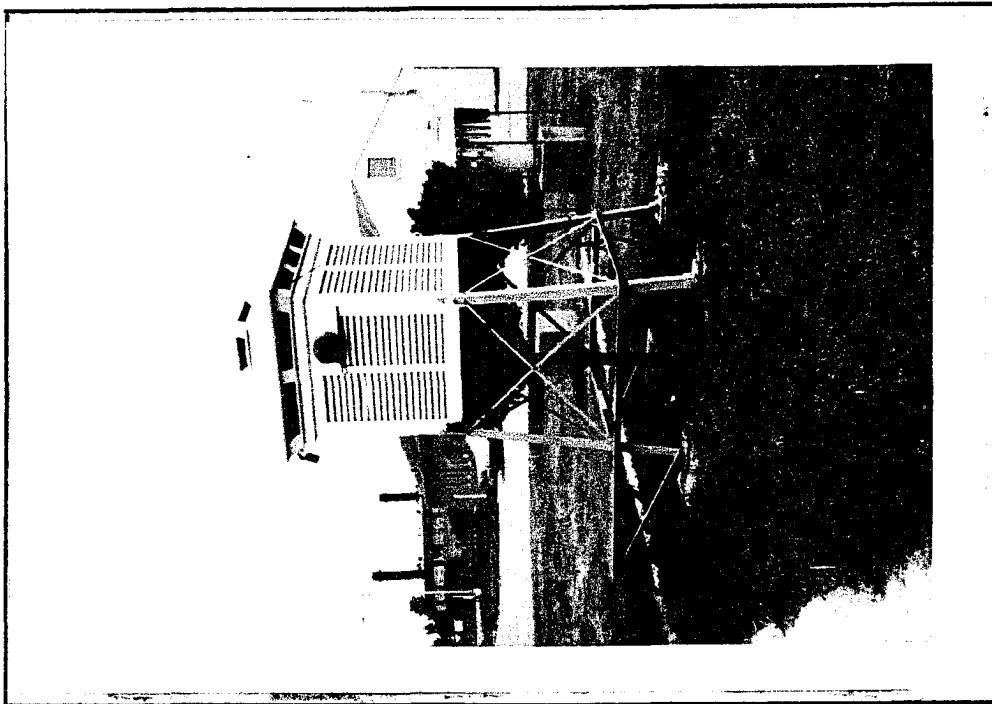
FIG. 3 METRO AIRPORT INSTRUMENT SITE



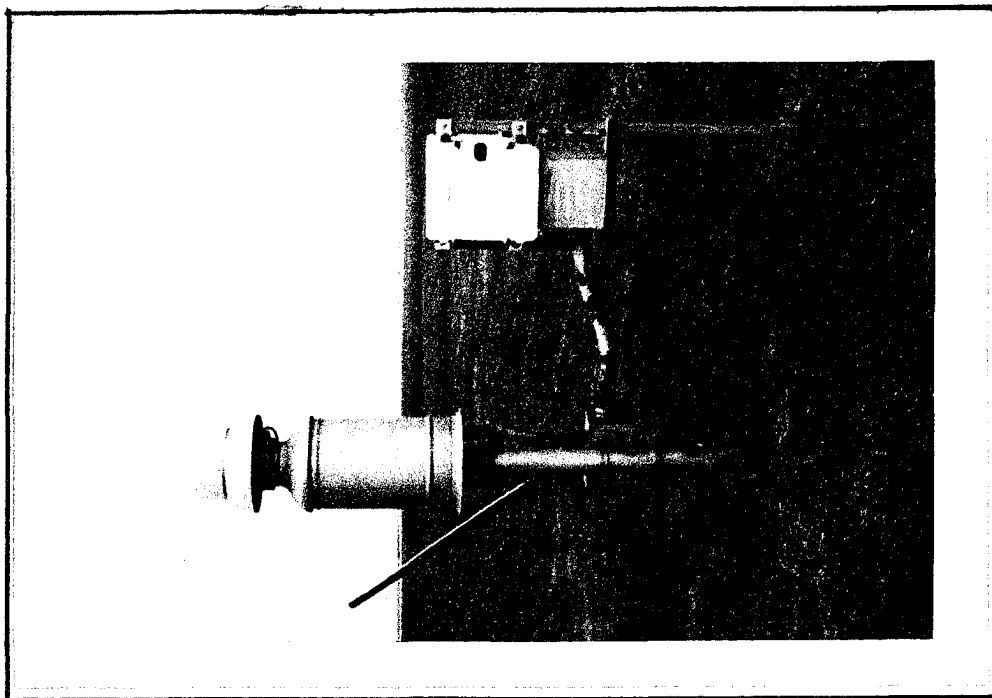
Photograph 1. Old Instrument Site at City Airport.



Photograph 2. Present Instrument Site at City Airport.



Photograph 3. Old Instrument
Site at Metro Airport.



Photograph 4. New Instrument
Site at Metro Airport.

the City and the Metro airports the site of the instruments as well as the height of exposure has not been the same during the period of study⁴.

At the City airport, the instrument site was located close to the old terminal building from 1960 to 1969 (figure 2). This site, with the building on one side and wild shrub growth adjacent to the instruments, did not have a good exposure. The raingage is still located here (photograph 1). The new site from 1967 is located on open land with good exposure (photograph 2).

The height of the instrument was 5 ft. until November 1960, when it was changed to 4.5 ft. In 1967 it was changed to 5 ft. A remote control psychrometer is used at the new site. It is possible that the change of site in 1967 may have some effect on the temperature measurements. The effect of the change in the height of the instrument may not be very significant since the height change was only 6".

The Metro airport instrument site also underwent a change in November 1961 (figure 3). The old site is in front of the old terminal building where the exposure is not very good (photograph 3). The new site is on the open fields with good exposure (photograph 4). The height of the wet and dry bulb thermometer used at the old site was 6 ft., while at the new site the height of the remote control hygrothermometer is 5 ft. Since the change was effected in 1961 at the beginning of the study period, it is assumed that the change is not significant as far as this study is concerned.

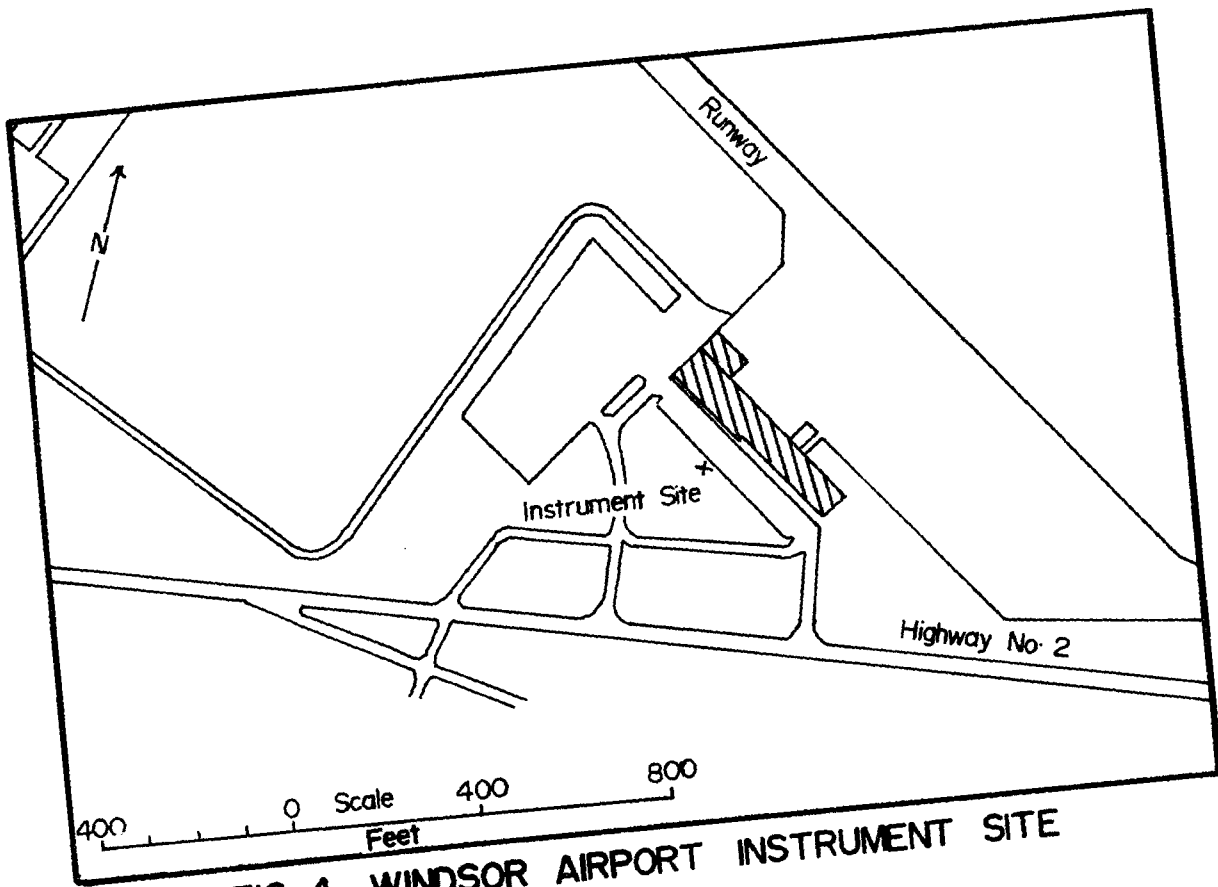
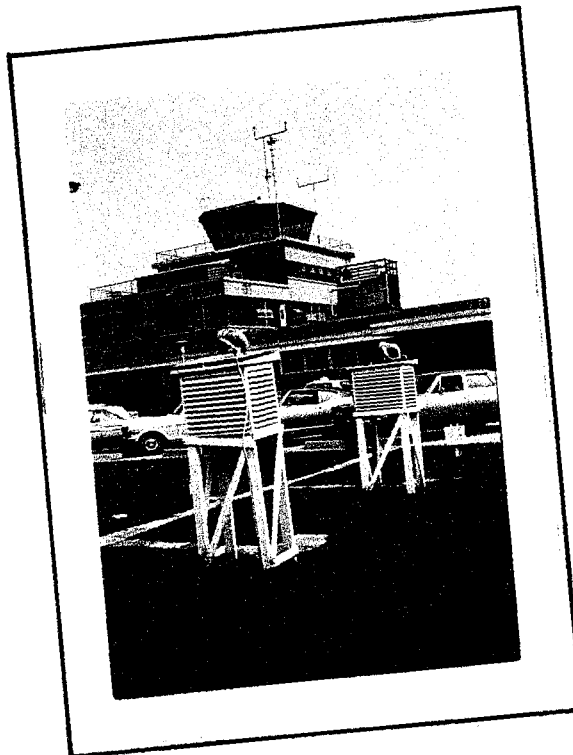


FIG. 4 WINDSOR AIRPORT INSTRUMENT SITE



Photograph 5. Instrument Site at Windsor Airport

In contrast to the two Detroit locations, the instrument site at the Windsor airport has not undergone any instrument changes during the study period. The instruments are located in front of the airport building (figure 4 and photograph 5). The remote control psychrometer and the motor psychrometer are used. The height of the instruments is 5 ft. There might be some local control by adjacent pavement and building on temperature, but it is assumed to be nil for this study.

3. Significance Tests

In order to test the significance of the temperature differences in the Detroit-Windsor area, three hourly temperature data (0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 hours) for the City airport, Metro airport and the Windsor airport for ten years from 1960 to 1969 were analyzed. The data for the City and Metro airports were obtained from the publication, Local Climatological Data of ESSA, U.S. Department of Commerce. The data for the Windsor airport were obtained from the records at the Windsor airport, Department of Transport, Government of Canada.

Statistical analysis was used to test for significant difference between the city and the country temperatures⁵. The difference between the city temperature and the country temperature (city temperature- country temperature) was used as the variate.

The null hypothesis is that the difference is zero. The alternate hypothesis is that the difference is greater than zero.

$$\text{i.e.} \quad H_0 : d=0$$

$$H_a : d>0$$

For a set of temperatures the corresponding temperature differences were found and the mean and the standard error for the differences were computed. The t-test was used to test whether the difference was significantly greater than zero. The value of t was calculated by the formula,

$$t = \frac{\bar{d}}{S_{\bar{d}}}$$

where, \bar{d} = mean temperature difference and $S_{\bar{d}}$ = standard error of difference. The calculated t was compared with the value of t obtained from statistical tables at the particular level of significance, and if the calculated t were greater than the value from the tables, the null hypothesis was rejected in favour of the alternate hypothesis.

In general the value of t depends on the number of degrees of freedom and therefore on the sample size n. Since the sample size used here is very large, the value of t is the same as that from the normal distribution tables. Hence for one tail test, $t=2.33$ at the 1% level for large n.

The paired data test as described, was applied to City-Metro, City-Windsor, and Metro- Windsor. In all three

cases a one-tailed test was used. For the first two, a one-tailed test was used since it was expected that the city temperatures will be higher than the country temperatures. For the third pair also, the one tailed test was used, since preliminary work indicated that the Metro airport temperature was higher than the Windsor airport temperatures.

The data were analyzed in the following ways:

- (i). The data for all the eight observation hours (0100, 0400, 0700, 1000, 1300, 1600, 1900 and 2200) were taken together and were analyzed for every year from 1960 to 1969. Comparisons were made between City and Metro, City and Windsor and Metro and Windsor locations.
- (ii). The data for each separate observation hour were analyzed for every year from 1960 to 1969 and comparisons made for the three pairs of stations.
- (iii). The data were analyzed on a monthly basis for all the eight observation hours taken together for the three pairs of stations for every year from 1960 to 1969.
- (iv). The data were analyzed on a monthly basis for each observation hour separately to show the variation with time for the month. This was also done for every year from 1960 to 1969.
- (v). Finally, the mean for each day was obtained from the eight, three hourly observations and the mean for the day was analyzed for the year and on a monthly basis for each year from 1960 to 1969. This was done in order to determine whether the same significance obtained in the analysis (i) and (iii)

above could be obtained by using a mean value of temperature for the day instead of several observations. It should be noted however, that the mean of the eight observations used here is different from and is more representative than the mean obtained from the maximum and minimum temperatures for the day.

A Fortran program was written for the IBM S/360 computer to perform the calculations mentioned in sections (i) to (v) above for the three pairs of stations. A listing of the program used appears in appendix B.

4. Multiple Regression Analysis

To determine the dependence of city-country temperature difference on various factors, i.e., temperature, windspeed, humidity and sky cover a multiple regression analysis was done⁵. Radiation and even the intensity of air pollution could be expected to influence the temperature difference of such a highly industrialized area as Detroit and Windsor. Since these data were not available for the three stations considered here, only the temperature, windspeed, vapour pressure and sky cover were used in the analysis. The empirical equation arrived at by Sundborg⁶ relating the temperature difference to these factors was used here. It is assumed that the temperature difference is related to these factors in a linear fashion given by the following expression:

$$D = A_0 + A_1T + A_2W + A_3V + A_4S$$

where,

D = Temperature difference in degrees Fahrenheit.

T = Temperature in degrees Fahrenheit.

W = Windspeed in miles per hour.

V = Vapour pressure in inches of mercury.

S = Sky cover in tenths.

and A_0 , A_1 , A_2 , A_3 and A_4 are constants which had to be determined by a multiple regression analysis.

Owing to the great volume of data that had to be handled, the above analysis was carried out only with data for two months for each of the three stations. The months selected were January and July which were considered typical winter and summer months respectively.

The data for the three stations were available as temperature, wind-speed, relative humidity and sky cover. The wind speeds for the Detroit stations were given in knots, while those for the Windsor station were given in miles per hour. They all had to be brought to a common unit, viz., miles per hour. Since relative humidity is a relative factor which depends not only on the amount of water vapour in the atmosphere, but also on the atmospheric temperature, the absolute humidity or the vapour pressure to which the latter is directly proportional was used. The conversion from relative humidity and temperature to vapour pressure was done by the Clapeyron-Clausius formula⁷ (Appendix A).

The relationship between the dependent variables

temperature, wind speed, vapour pressure and sky cover was determined by multiple regression analysis. When the temperature difference between two particular stations was considered, the data were available for both stations, but the values corresponding to both stations were not the same and therefore the average of the two values was used in the analysis.

The coefficients were determined for the whole day taking the data for all eight observation hours and also for each observation hour separately. Analysis was done for the months January and July separately and in each case with the two differences in temperature, viz., City-Metro and City-Windsor.

A listing of the Fortran program which was written to calculate the coefficients by multiple regression analysis is given in Appendix C.

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6. Landsberg, H. E. "The Climate of Towns," in Man's Role in Changing the Face of the Earth. ed. Thomas, W. L. Chicago: University of Chicago Press, 1956. Pp. 584-605.
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CHAPTER IV

ANALYSIS OF RESULTS

The results obtained from the significance tests provide two sets of information: (1) the number of times the results are statistically significant, (2) the actual size of the mean difference. In the case of the former, a level of significance of 1% is used in order to have reasonably good confidence in the results. For each period considered, there are ten possible times the difference can be significant, since the data for each year was analyzed separately. The number of times the difference is significant is considered as a percentage of this total in the following discussion. This percentage is tabulated in tables 1(a,b,c) for the three pairs of stations City-Metro, City-Windsor and Metro-Windsor. It should be pointed out that in addition to considering each observation hour separately: (1) all eight observations are taken together as eight different observations for the day and referred to as "all day and (2) the mean of all the eight observations are taken as the average for the day and referred to as "average".

The magnitude and the variation of the mean difference is analyzed. The yearly variation of the mean difference (figure 5) is based on the all day analysis for each year. The monthly variation of the all day mean

difference and the variation with time for the year and for each season are based on the average for all ten years.

The influence of temperature, wind speed, vapour pressure and sky cover on the temperature difference is considered. The constants A_0 , A_1 , A_2 , A_3 and A_4 obtained by multiple regression analysis are tabulated in table 2(a,b).

1. Significance Tests

(i) Yearly Analysis

In the case of the all day analysis for each year for City-Metro, it is found that the frequency of significance is 100%. When the same test is repeated using the mean of the eight observation hours for each day, i.e. the average, it also shows the frequency of significance to be 100% (table 1a). The corresponding tests applied to City-Windsor yield the same results. The two country combination Metro-Windsor shows a frequency of significance of 70%. The analysis using the average also exhibits similar results. In all three cases the analysis for all day (all eight observation hours taken together) is identical to that of the results from the analysis of the average.

(ii) Monthly Analysis

Monthly analysis for all day for City-Metro shows the frequency of significance to be 100% during the months of May, August, September and October. In February and March the frequency of significance is only 60%, which is the minimum

Table 1(a)

Frequency of Significance of Temperature Difference
(in percent) for City-Metro.

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day	Avrg
Year	100	100	100	70	30	20	100	100	100	100
Jan.	70	70	70	40	30	20	80	70	90	80
Feb.	60	50	50	10	10	10	40	60	60	40
Mar.	60	60	70	30	20	10	50	60	60	60
Apr.	70	70	80	20	20	20	50	80	80	60
May	90	100	80	40	30	20	50	90	100	70
June	80	90	90	60	30	10	50	80	90	90
July	90	90	90	50	20	10	50	100	90	90
Aug.	100	100	100	70	40	10	70	100	100	100
Sep.	100	100	100	60	30	30	90	100	100	100
Oct.	100	100	100	60	40	30	100	100	100	100
Nov.	80	80	80	60	30	30	80	80	80	80
Dec.	60	50	50	40	30	30	70	80	90	60

Table 1(b)

Frequency of Significance of Temperature Difference
(in percent) for City-Windsor.

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day	Avrg
Year	100	100	100	100	100	100	100	100	100	100
Jan.	90	90	70	60	60	90	100	100	100	100
Feb.	80	70	70	50	80	80	80	90	100	100
Mar.	100	90	90	80	100	100	100	90	100	100
Apr.	100	100	100	80	90	80	90	100	100	100
May	100	100	80	90	100	100	100	100	100	100
June	100	80	90	90	100	90	100	100	100	100
July	100	90	90	80	80	90	90	100	100	100
Aug.	100	90	90	90	100	90	100	100	100	100
Sep.	100	90	80	90	100	90	100	100	100	100
Oct.	90	80	90	90	90	90	100	100	100	100
Nov.	90	80	90	70	100	100	100	100	100	100
Dec.	100	80	80	70	80	80	90	100	100	100

Table 1(c)

Frequency of Significance of Temperature Difference
(in percent) for Metro-Windsor.

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day	Avrg
Year	30	20	20	60	100	100	70	60	70	70
Jan.	10	20	10	20	90	100	40	10	70	20
Feb.	20	20	20	40	90	80	60	40	80	80
Mar.	40	40	10	60	90	90	70	60	80	70
Apr.	40	20	20	70	90	80	60	50	80	70
May	30	20	20	60	90	90	50	40	60	60
June	20	10	20	40	60	90	70	40	50	50
July	10	10	00	50	70	70	60	40	60	50
Aug.	10	00	00	40	80	80	60	30	70	70
Sep.	00	00	00	40	90	80	50	00	40	40
Oct.	00	00	00	20	90	80	40	00	20	20
Nov.	10	00	10	20	80	90	20	20	30	20
Dec.	00	10	00	20	80	90	30	20	40	40

for the year (table 1a). The averages masks these differences in some cases. The comparison indicates a smaller frequency of significance when testing is done with the averages. During five months of the year the frequencies differ. In some cases it is large, as in May where the average frequency of significance is 70%, while the all day frequency is 100%. The corresponding test for City-Windsor for all day as well as for the average reveals identical results with the City temperature being higher than the Windsor temperature 100% of the time for all months (table 1b). In the analysis for the two country locations Metro-Windsor, the Metro temperatures are significantly higher than the Windsor temperatures in 80% of the cases in March, April and May (table 1c). October with 20% frequency has the lowest value. The averages do not tally with the all day results for five months of the year with the difference being greatest in January.

(iii) Analysis for Each Observation Hour

Significance testing was done for the temperature difference at each observation hour (a) with the data for the whole year and (b) with the data for each month separately.

(a) Significance testing for the year indicates a frequency of 100% except at hours 1000, 1300 and 1600 with 70%, 30% and 20% frequency of significance respectively in the case of City-Metro. These hours are the time when city-country

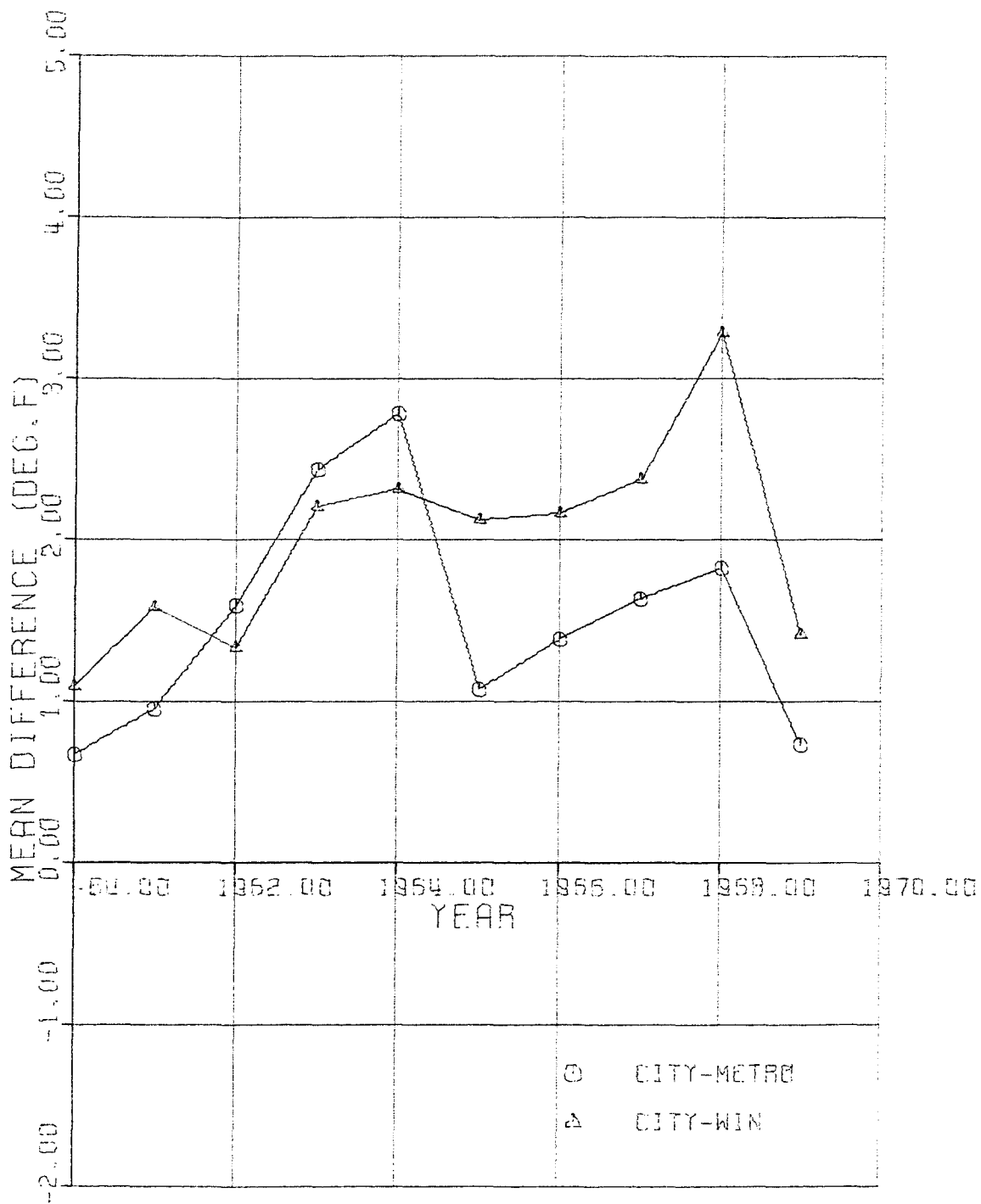
difference is least significant.

In contrast to City-Metro, City-Windsor figures illustrate that the frequency of significance is 100% throughout the day at all hours. The corresponding test for Metro-Windsor indicates a reverse situation to that of City-Metro. At hours 1300 and 1600 the frequency of significance is 100%. At hours 0400 and 0700 the frequency of significance is least - only 20%.

(b) The results of the monthly analysis for each observation hour for City-Metro during August, September and October show that the frequency of significance is 100% at hours 2200, 0100, 0400 and 0700 showing the heat island of the city during the night. February with the frequency of significance of 10% at 1000, 1300 and 1600 hours is the month where the differences are significant the least number of times, particularly during the mid-day (table 1a).

The corresponding test for City-Windsor shows that for the month of February at hour 1000, the difference is significant the least number of times with 50% frequency. 1300 and 1600 are the hours when the frequency of significance is least for City-Metro, while 0700 and 1000 are the hours when the frequency of significance is least for City-Windsor.

Since the Metro-Windsor comparison is less important in this study of the urban heat island, it will not be discussed any further.



YEARLY VARIATION OF MEAN DIFFERENCE

FIGURE 5*

*
All graphs were plotted using an IBM S/360 computer and a Calcomp plotter.

2. The Variability of the Urban Heat Island

(i) Average Mean Difference

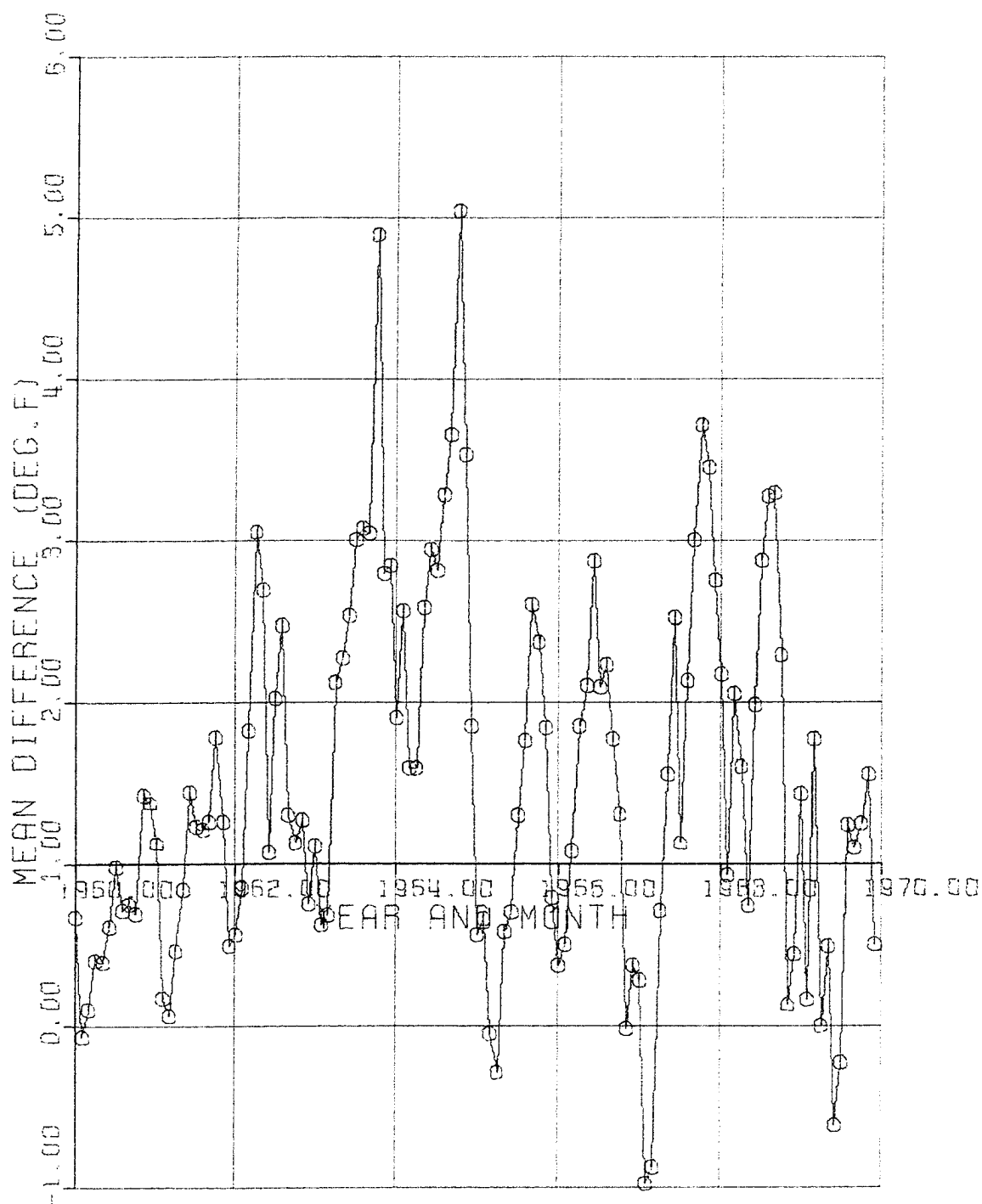
The average mean difference for the ten years for City-Metro is 1.5°F and for City-Windsor is 2.0°F (Appendix E). Landsberg¹ gives a figure of 1.3°F for a city with a population of over one million. The average mean difference of 1.5°F for City-Metro and 2.0°F for City-Windsor may be due to the physical structure of the city with high vertical development in the center of the city. The artificial heat generation in the Detroit and Windsor area would be rather high, considering the high degree of industrialization particularly of that of the automobile industry in the area. Oke² is of the opinion that the heat island in Hamilton, Ontario is mainly due to the heat generated from the steel industries there. The city's population of 4.5 million would also have its effects, though the influence may be considerably small. The pollution haze produced by the various human activities would reduce the incoming solar radiation and also increase the heat from counter radiation.

It is not possible to assess the effects of each of these factors on the urban heat island due to its complexity. Analysis of this nature is beyond the scope of the present study.

(ii) Year to Year Variation of Mean Difference

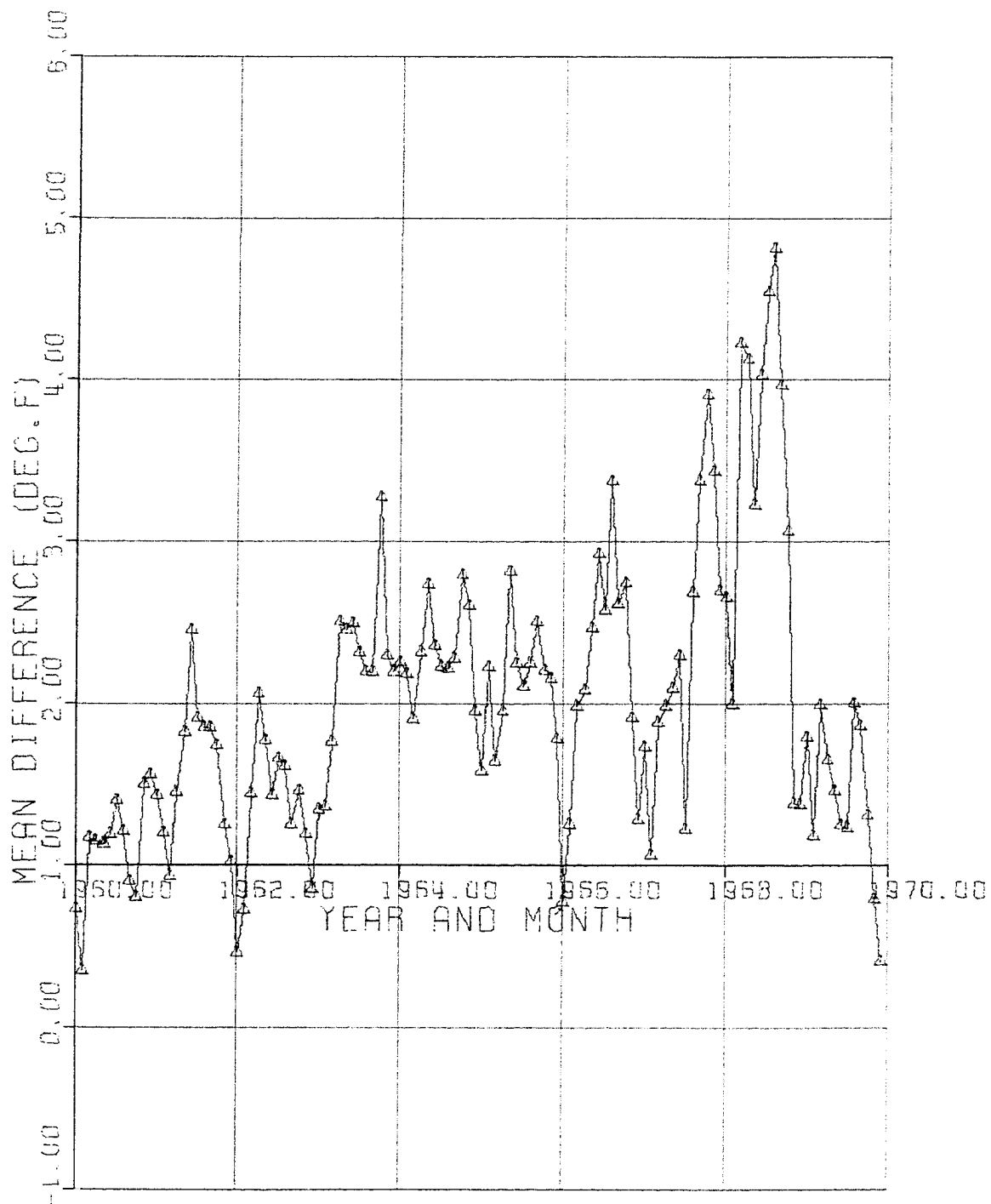
The year to year variation of mean difference from 1960 to 1969 is shown in figure 5. The maximum difference of 3.29°F is seen between City-Windsor in 1968. The minimum difference of 0.67°F is found between City-Metro in 1960. The City-Metro mean difference increases steadily from 0.67°F in 1960 to 2.78°F in 1964 and then registers a sharp fall of 1.07°F in 1965. The mean difference starts rising again rather slowly to 1968 and then falls slightly in 1969. The City-Windsor mean difference fluctuates less than that of City-Metro. There is a steady rise in the mean difference. Except for a small fall in 1962, the mean difference keeps rising though very slowly upto 1967. There is a marked increase from 2.37°F in 1967 to 3.29°F in 1968. Finally it drops sharply to 1.41°F in 1969.

It is difficult to explain the causes of these fluctuations. It seems to show a random fluctuation which is commonly seen with many climatic elements. Trends could be traced by a time series analysis³, if the study were based on a longer period of time. It is possible to speculate on the causes of these changes in a very general way, such as local site changes. The instrument site change at the Metro airport took place in 1961 and at the City airport in 1967, but from the graph it is not possible to say whether these have had any effects on the mean difference. The constantly changing urban pattern is another factor which would affect



MONTHLY VARIATION OF MEAN DIFFERENCE
-1960 THROUGH 1969 CITY-METRO

FIGURE 6a



MONTHLY VARIATION OF MEAN DIFFERENCE
-1960 THROUGH 1969 CITY-WIN

FIGURE 6b

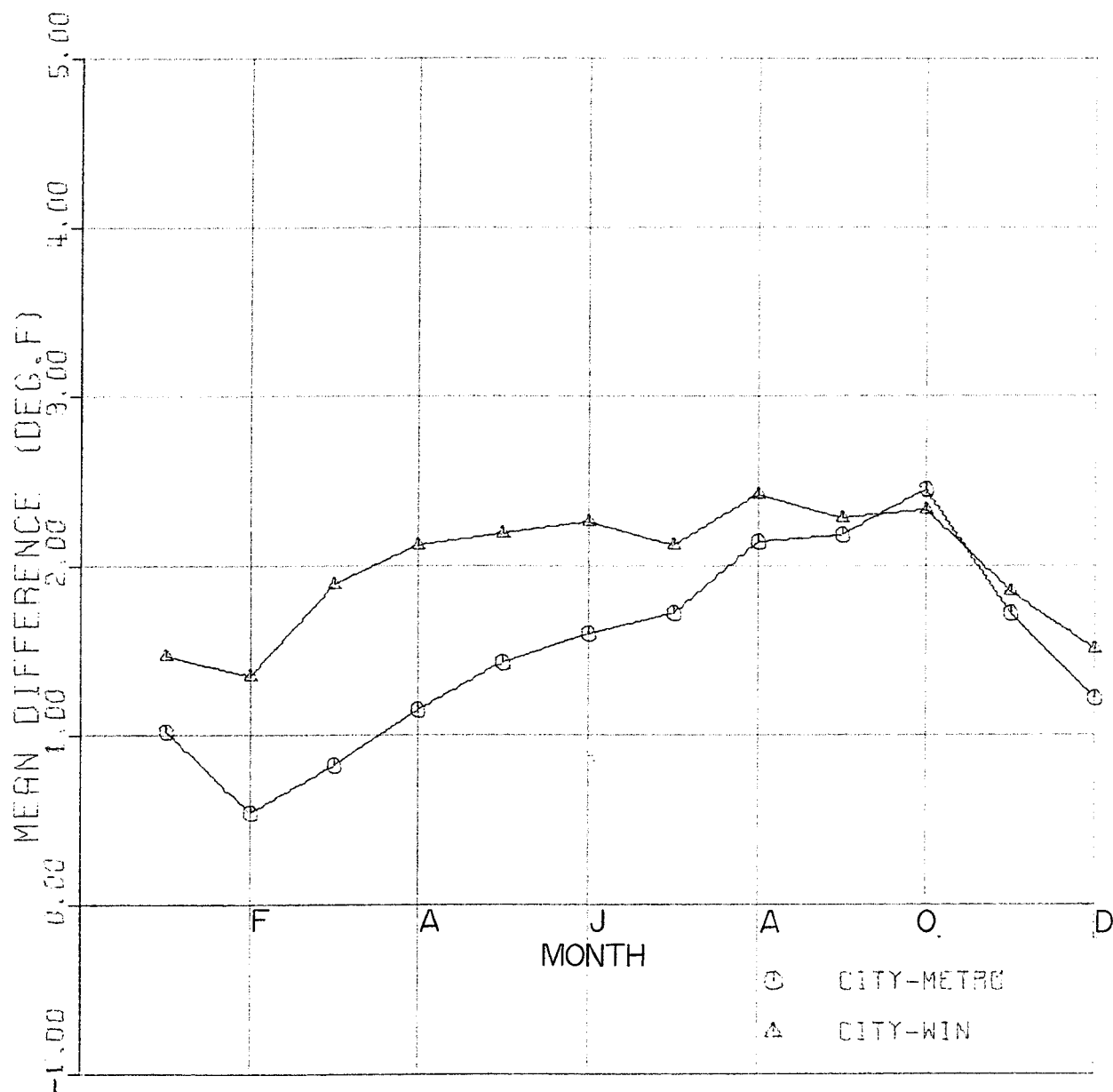
the mean difference.

Figures 6(a,b) show the month to month variation of mean difference from 1960 to 1969 for City-Metro and City-Windsor. The mean differences fluctuate considerably from month to month, but the fluctuation in the case of City-Metro is much greater than that for City-Windsor. Some months consistently have high differences as in the case of October. In October, 1965 the mean difference is as much as 5.0°F for City-Metro, while February, 1967 has a negative mean difference of -1.0°F for the same.

(iii) Monthly Variation of Mean Difference

The monthly variation of the all day mean difference (figure 7) shows that the city location is warmer than the country locations during all months. The City-Metro and the City-Windsor mean differences follow the same general trend. City-Windsor has a maximum (2.45°F) in fall and a minimum (0.54°F) in winter. City-Metro exhibits a maximum (2.42°F) in summer and a minimum (1.35) in winter. Other studies have shown that the annual march of city-country temperature differences vary from city to city. For example in Paris, the maximum is in fall (2.2°F) and the minimum in summer (1.2°F). Tulsa, Ok. has a maximum (1.3°F) in fall and a minimum ($.7^{\circ}\text{F}$) in spring¹.

Although the maximum differences are almost equal in both cases, this is not so with the minimum difference which is lower in the case of City-Metro. The City-Windsor curve is



MONTHLY VARIATION OF MEAN DIFFERENCE
(AVERAGE OF TEN YEARS)

FIGURE 7

smoother with less variation than in the case of City-Metro, which shows a greater range of fluctuation. But both curves follow the same general trend. There is a gradual rise from the low mean difference of February to a high mean difference in early fall. The mean differences start falling with the beginning of winter.

The behaviour of the mean difference cannot be explained entirely, but such factors as radiation, cloud-cover, wind speed, temperature and site conditions apparently do have effects on the seasonal variation of the mean temperature differences. It is not possible to evaluate the effects of radiation, since radiation measurements are not available from the station network.

In analyzing the effects of clouds on temperature differences, it is interesting to note that February, which records the lowest mean difference in both city-country comparisons, coincides with the greatest number of days (25) with more than 8/10 cloud cover⁴. Many heat island studies on large as well as small cities have shown the effect of clouds on reducing the temperature difference between a city and the surrounding countryside. This is in agreement with the results obtained by multiple regression analysis of the effect of sky cover on the temperature difference, especially during the nocturnal hours. This is discussed in greater detail in a later section (page 61). Since the winter months, and particularly February, have the greatest number of days with more than 8/10 cloud cover, it is reasonable to conclude that the cloud cover plays a great part

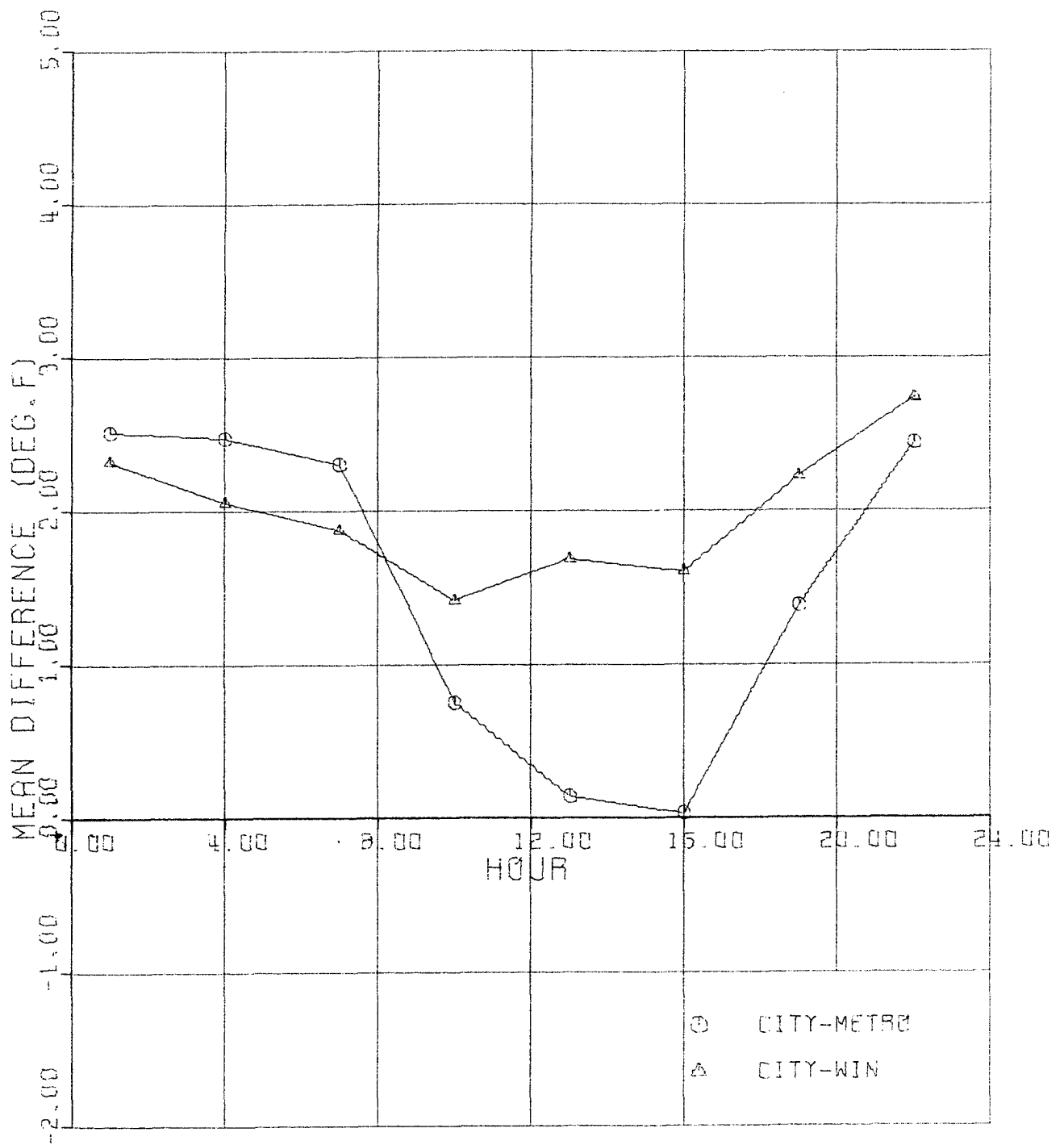
in lowering the temperature difference between city and country locations.

Winds also have an effect in reducing the temperature difference. The winds are predominantly from the south-west quadrant in this area. Also February is the month with the greatest storm activity⁴. The low mean difference also coincides with the period of time when Lake St. Clair is ice covered and any lake effect is therefore non-existent. The temperature difference is also influenced by the actual temperature. The temperature has an increasing effect in summer, but this effect is negligible in winter as revealed by the multiple regression analysis (page 64). It is possible that all these factors interact to minimize the temperature difference between city and country-side during the winter months.

(iv) Variation of Mean Difference with Time of Day

Figure 8 shows the variation of mean difference with time of day. City-Metro and City-Windsor both exhibit a similar pattern in the variation of mean difference. The differences are large in the nocturnal hours from 2200 to 0700. The time of least difference is in the afternoon hours at 1600.

The typical city-country pattern is well depicted in the case of City-Metro with marked high difference in the early morning hours when the urban heat island is well developed with a high of 2.5°F at 0100. In contrast to this the City-Windsor mean difference curve is smoother with mean difference remaining high and almost constant. There appears



VARIATION OF MEAN DIFFERENCE WITH TIME
FOR THE YEAR (AVERAGE OF TEN YEARS)

FIGURE 8

to be a well developed heat island at all hours. The variation in the intensity of the City-Windsor difference through the day is not as well marked as in the City-Metro difference.

City topography and surface cover apparently influence the urban heat island. However, local topography does not vary significantly in this area and therefore it is reasonable to assume that it does not affect the city-country temperature difference as much as the other variables. It is also necessary to mention the urban characteristics of the areas surrounding the Metro airport location. They are different from the Windsor airport characteristics. The City-Metro differences indicate that there is an intense heat island at night and a gradual dissipation of the heat island during the day time with zero difference at 1600 hour. On the other hand, the City-Windsor differences show a well developed heat island at night with a relatively less intense heat island during the day. This apparent anomaly is probably due to such factors as the influence of Lake St. Clair and the surrounding paved surfaces on the Windsor temperatures, particularly during the summer. No investigation of this anomaly has been undertaken.

The physical structure of the cities of Detroit and Windsor with tall concrete buildings close together, is probably an important factor as has been indicated elsewhere. In the morning, the sun's rays strike both the city and the country-side at a low angle. When this happens in the country-side much of the radiation is reflected back into space. In the

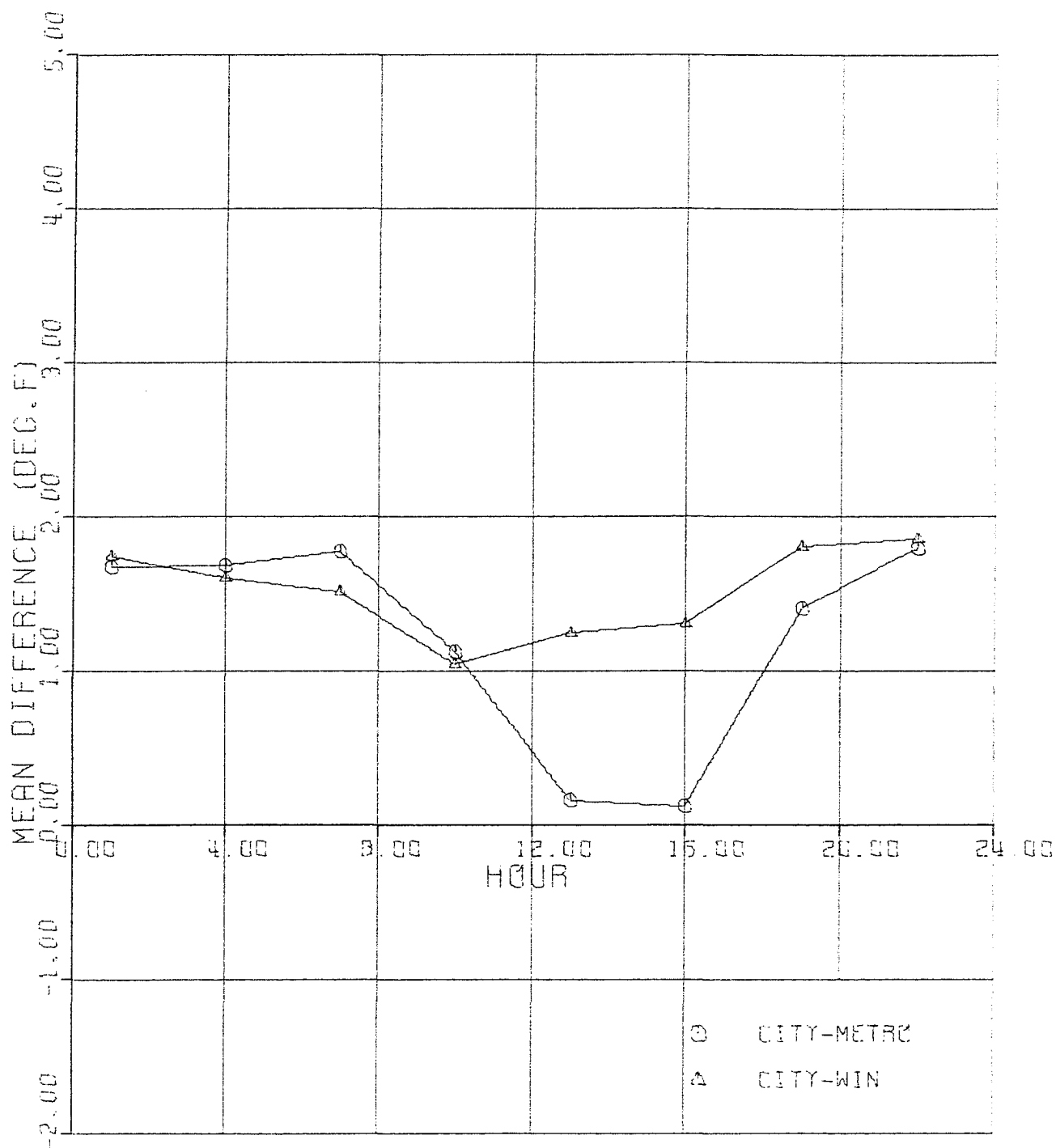
city when solar radiation strikes the vertical walls of buildings, there is much reflection and re-reflection from buildings resulting in most of the radiation being trapped and stored as heat in the street and building materials. As the day progresses, the direct beam solar radiation does not strike the vertical walls at a large angle. The increased intensity of the sun's rays on equal horizontal areas increases the temperature at both places lowering the city-country temperature differences. Later in the day, the same situation exists as in the morning and the differences begin to increase. At night, the stored daytime solar energy from the city surfaces is released, resulting in the nocturnal urban heat island⁵. Thus radiation relations help to explain an urban heat island, although in this study not the difference for City-Windsor.

(v) Variation of Urban Heat Island for the Four Seasons

The results of the analysis on a monthly basis for every three hours are shown in figures 9-20. They are grouped seasonally; December, January and February are considered winter months; March, April and May the spring months; June, July and August the summer months; and September, October and November the fall months.

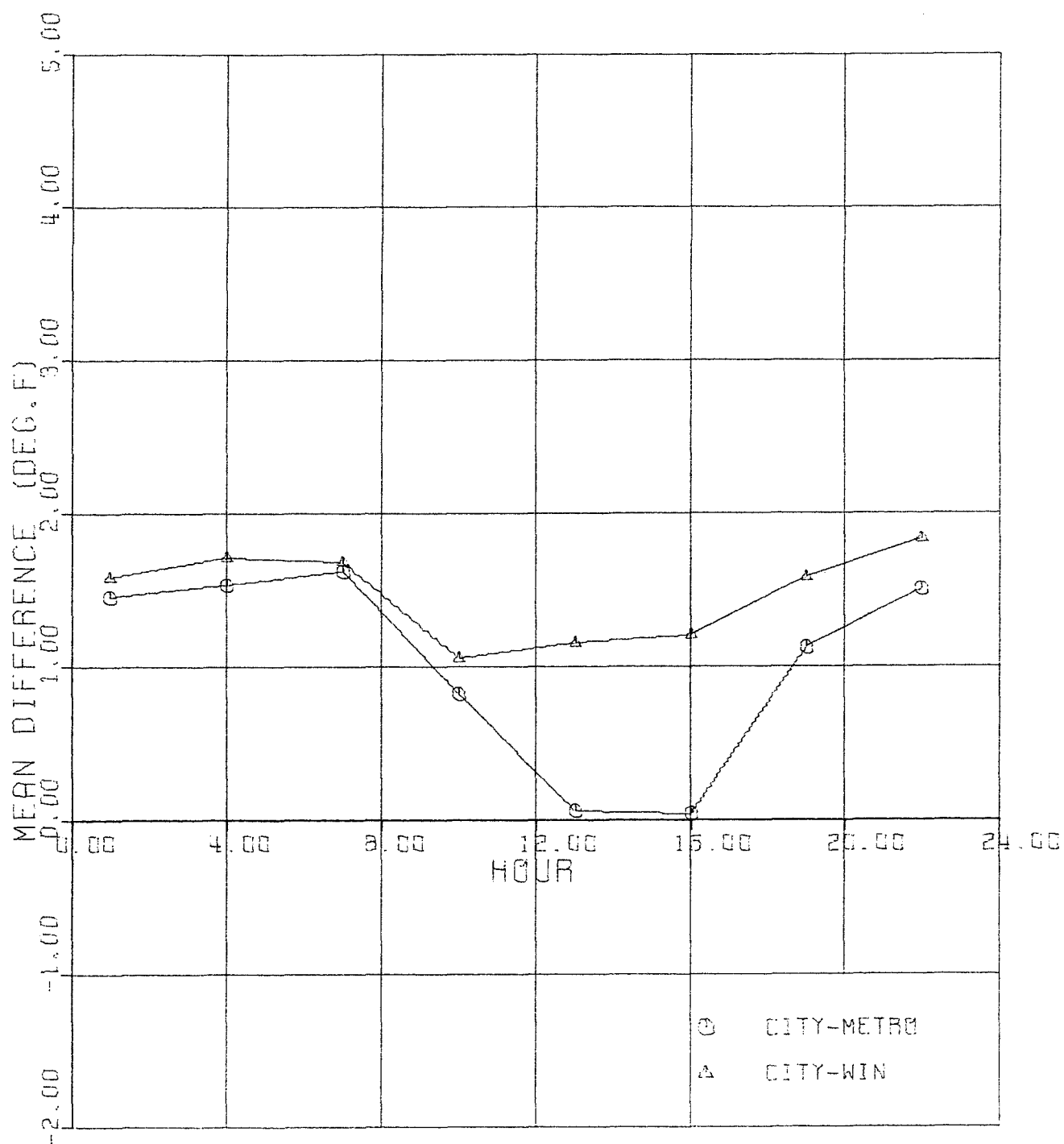
(a) Winter

All months show low mean differences (figures 9, 10, 11). The general pattern illustrates a well developed heat



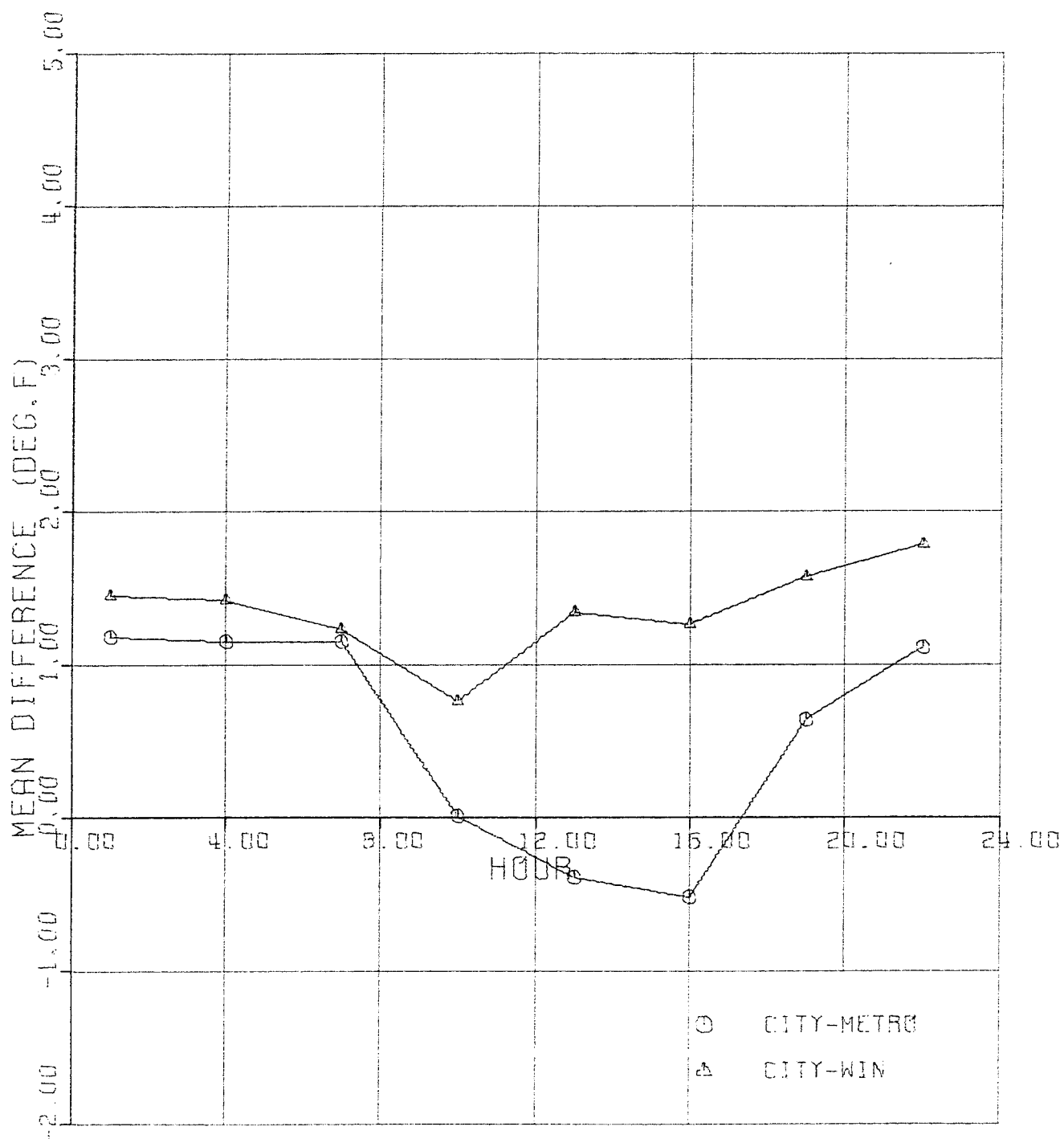
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR DECEMBER (AVERAGE OF TEN YEARS)

FIGURE 9



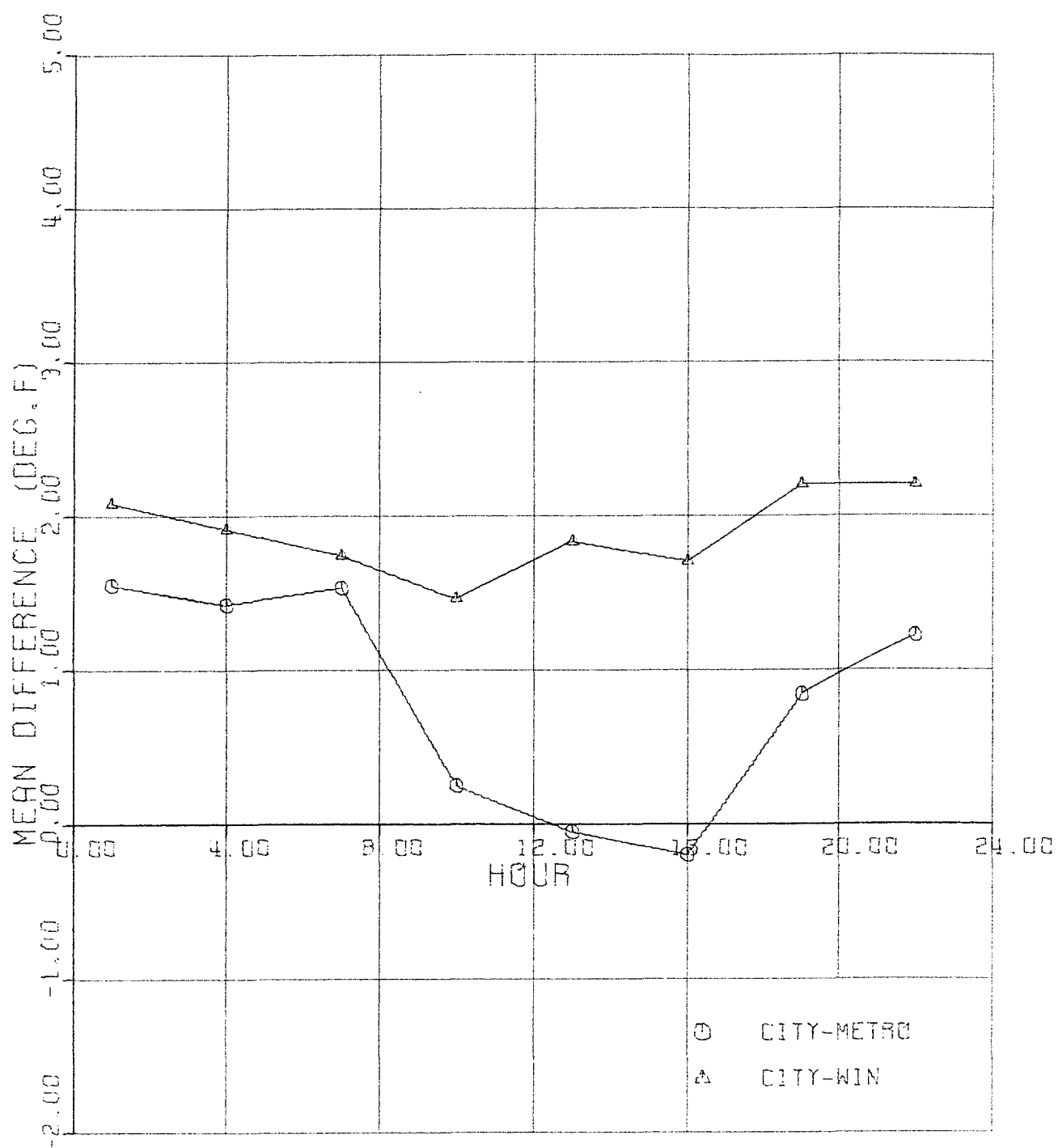
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR JANUARY (AVERAGE OF TEN YEARS)

FIGURE 10



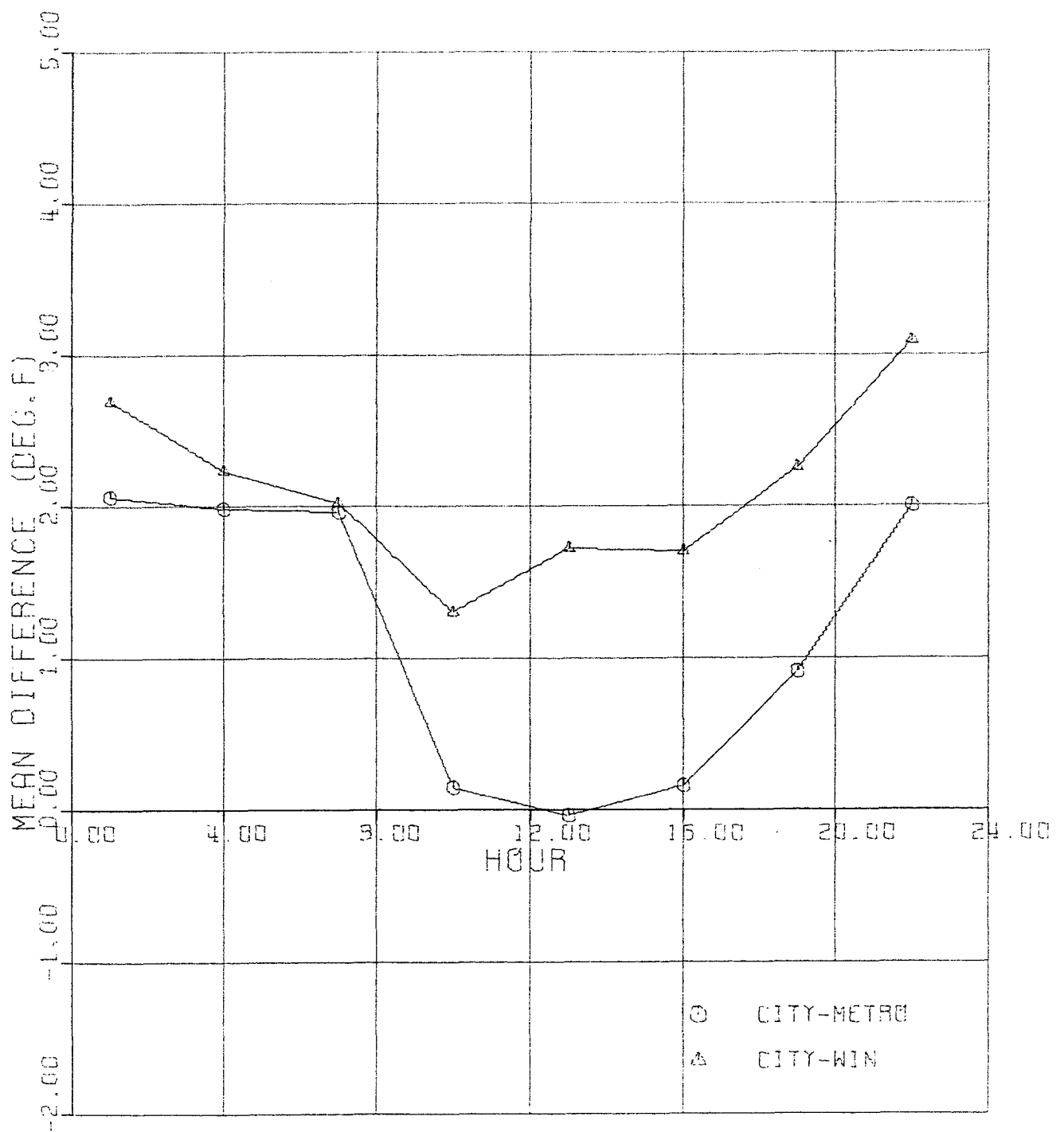
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR FEBRUARY (AVERAGE OF TEN YEARS)

FIGURE 11



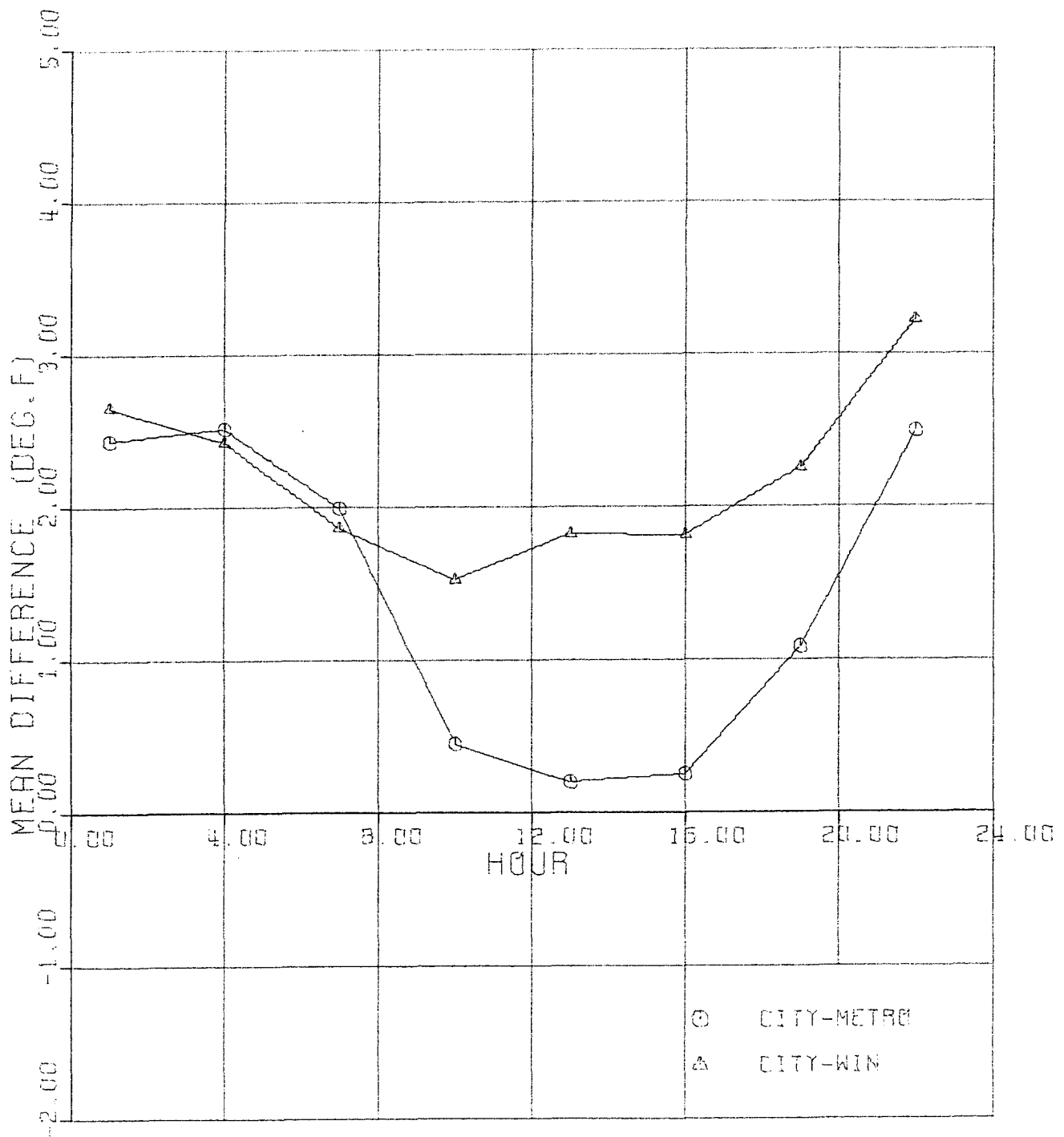
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR MARCH (AVERAGE OF TEN YEARS)

FIGURE 12



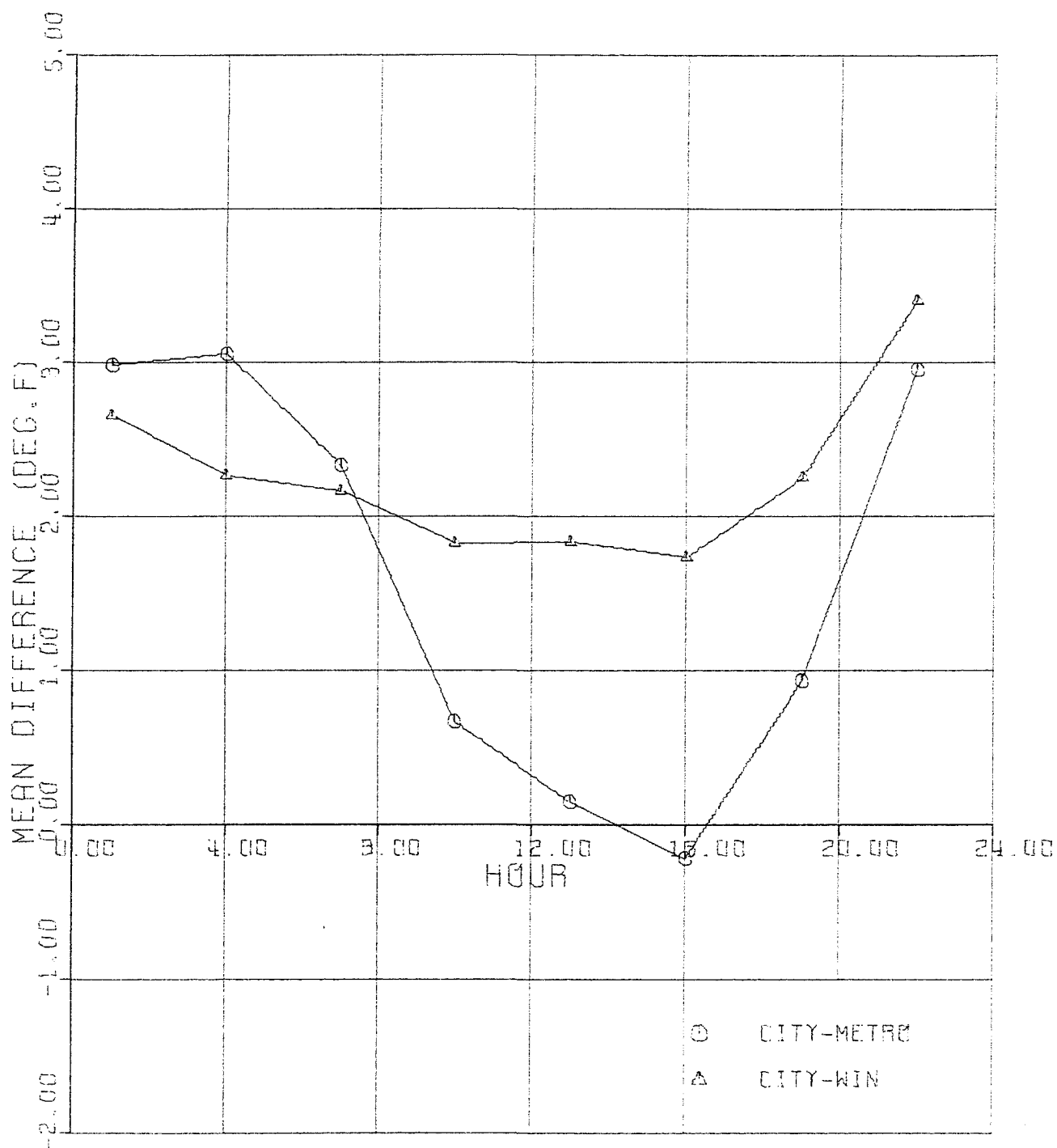
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR APRIL (AVERAGE OF TEN YEARS)

FIGURE 13



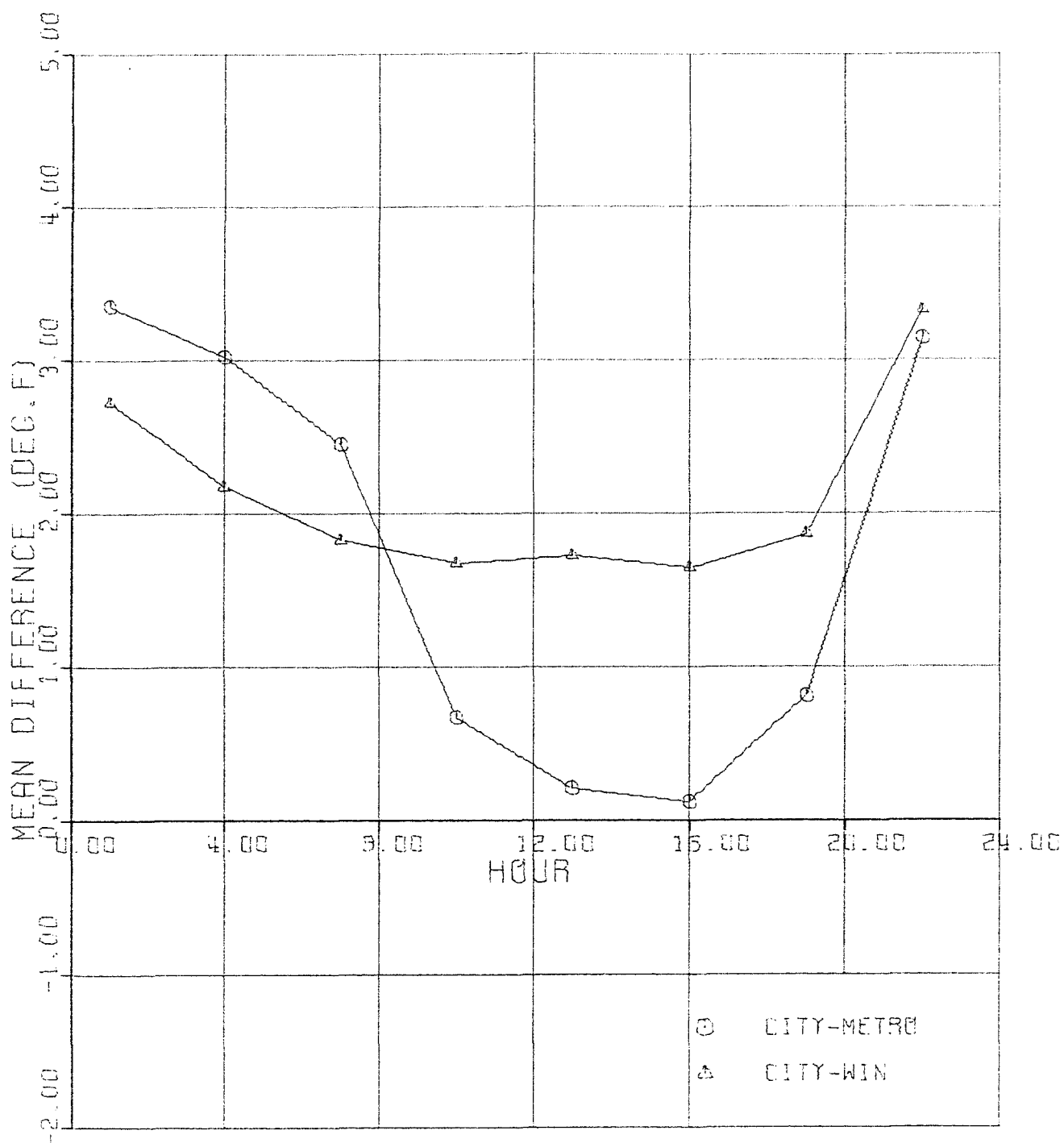
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR MAY (AVERAGE OF TEN YEARS)

FIGURE 14



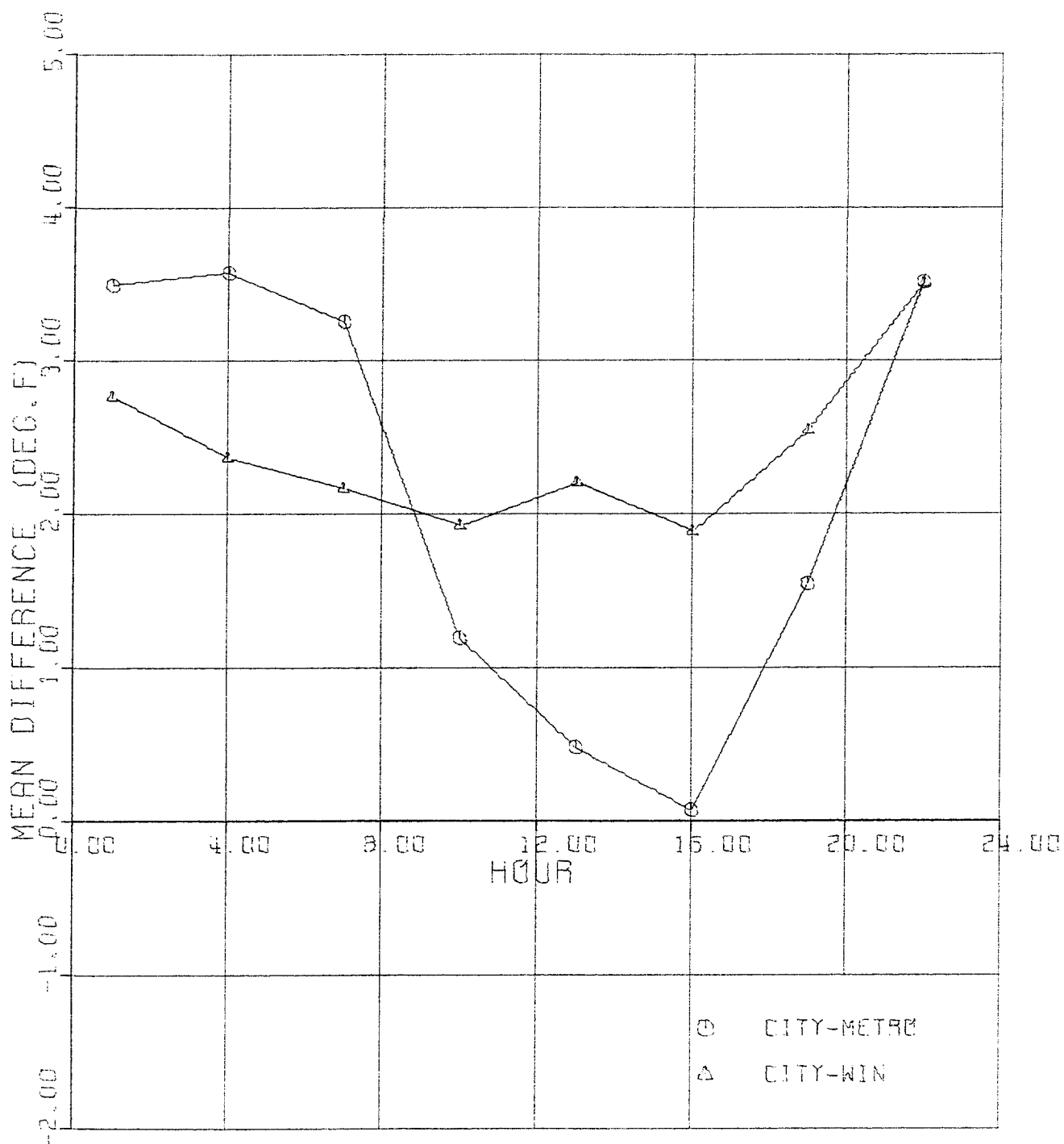
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR JUNE (AVERAGE OF TEN YEARS)

FIGURE 15



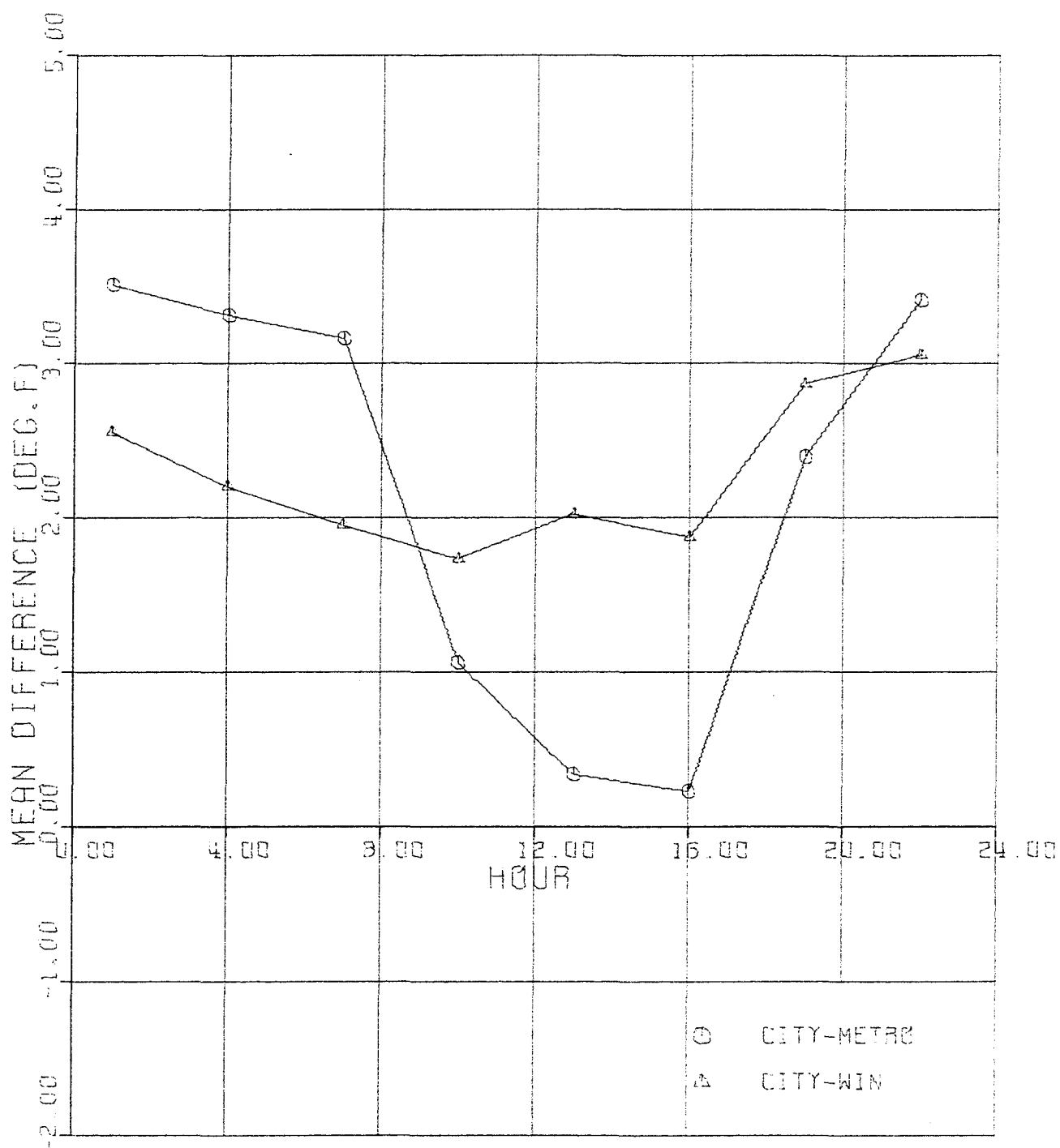
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR JULY (AVERAGE OF TEN YEARS)

FIGURE 16



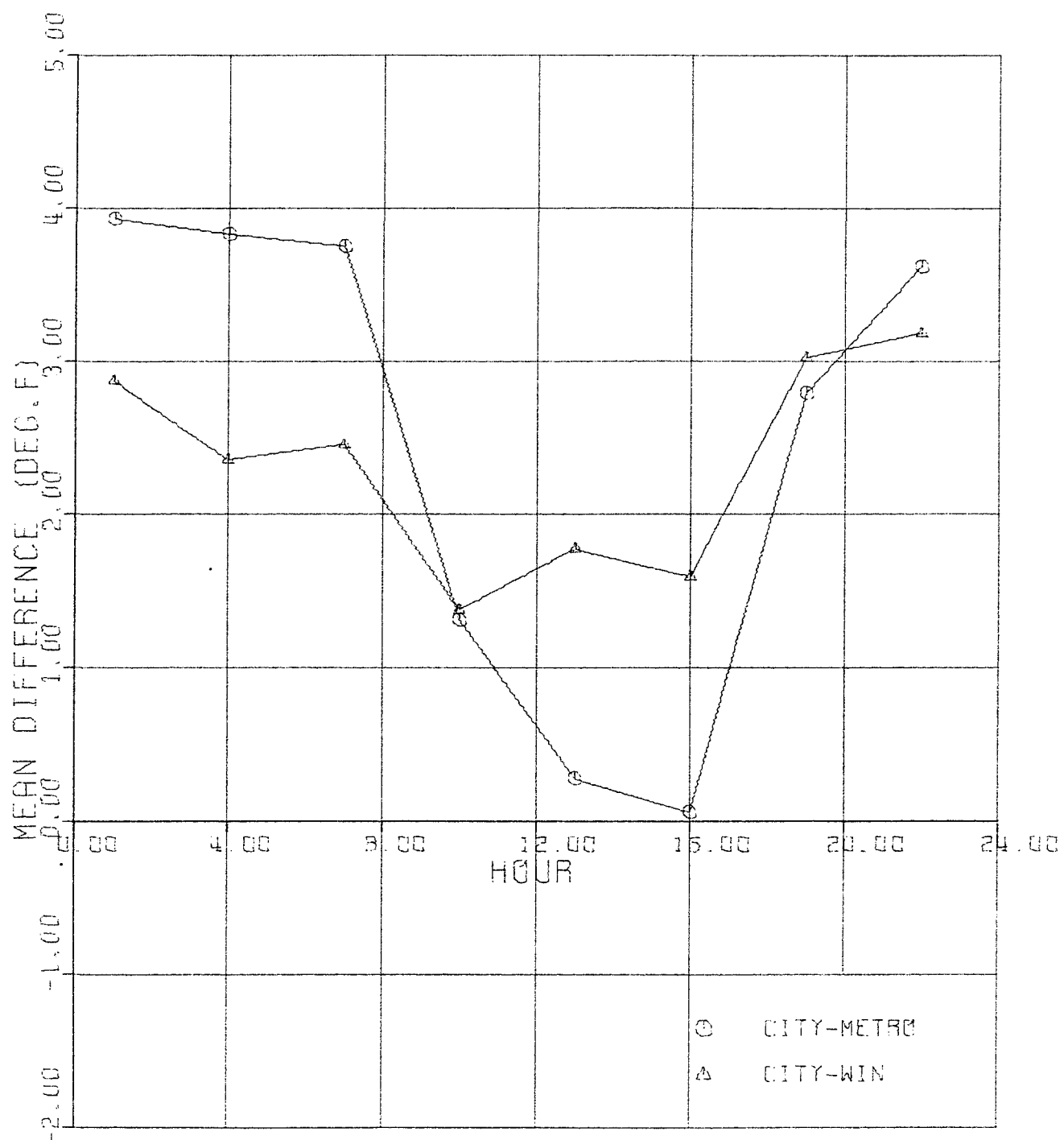
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR AUGUST (AVERAGE OF TEN YEARS)

FIGURE 17



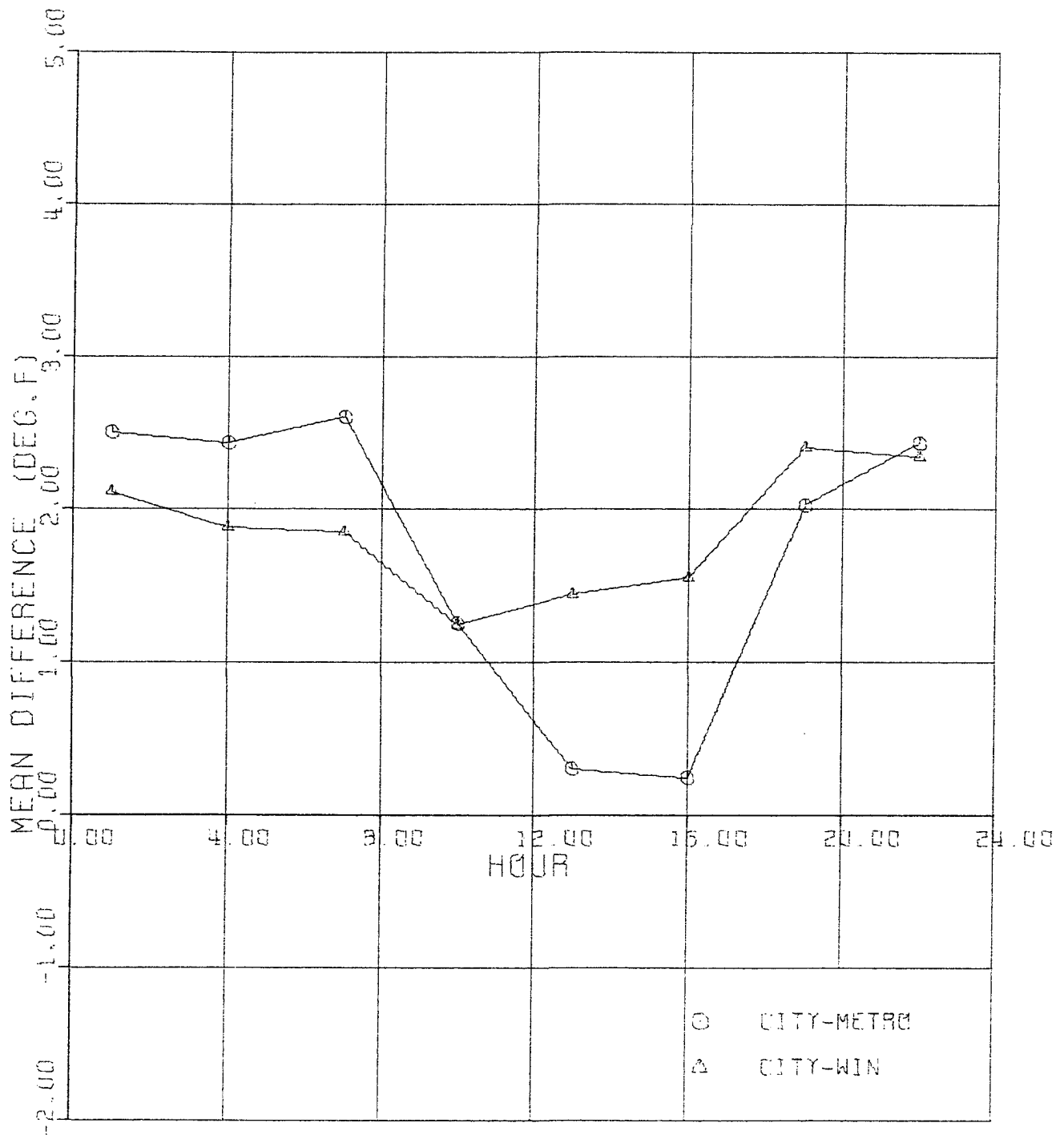
VARIATION OF MEAN DIFFERENCE WITH TIME
FOR SEPTEMBER (AVERAGE OF TEN YEARS)

FIGURE 18



VARIATION OF MEAN DIFFERENCE WITH TIME
FOR OCTOBER (AVERAGE OF TEN YEARS)

FIGURE 19



VARIATION OF MEAN DIFFERENCE WITH TIME
FOR NOVEMBER (AVERAGE OF TEN YEARS)

FIGURE 20

island during the night for City-Metro and City-Windsor. There is an almost complete lack of the urban heat island (fig.9,10) and a possible formation of a 'cold island' (fig.11) during the afternoon hours for City-Metro. The City-Windsor curve shows a well-developed heat island at all hours, with the minimum difference at 10 a.m.

(b) Spring

The urban heat island is well developed with higher differences than in winter during the night. Afternoon hours show no heat island development for City-Metro while City-Windsor exhibits a heat island of considerable magnitude even during the daytime (fig. 12,13,14).

(c) Summer

The heat island development is of considerable magnitude. City-Metro shows a rapid drop in the difference with the heat island almost nil at hour 1600, whereas City-Windsor still has a well-developed heat island even during the afternoon hours (fig. 15,16,17).

(d) Fall

The fall months in which the maximum mean differences occur, also show the maximum contrast between the day and night hours. The heat island in the case of City-Windsor does not undergo any appreciable reduction during the daytime as in the other seasons (fig. 18,19,20).

3. Multiple Regression Analysis

The influence of temperature, wind speed, vapour pressure and sky cover on the temperature differences is determined by the magnitude and the sign of the coefficients A_1 , A_2 , A_3 and A_4 respectively. The coefficients have been tabulated in tables 2(a,b) for the two pairs of stations City-Metro and City-Windsor. The following observations can be made from these tables.

It is seen from the coefficients obtained by analyzing the data for all eight observation hours, that the effect of the sky cover is to decrease the temperature difference both in winter and summer. The temperature and wind speed also tend to decrease the difference when they increase in winter, but have almost negligible effect on the summer temperature difference. The effect of vapour pressure variations is quite small as shown by the very small coefficients, and therefore can be neglected. All the above effects apply to both city-country combinations.

The analysis for each observation hour illustrates the influence at different times of the day. The sky cover tends to decrease the temperature difference in the evening and night hours in both seasons. During the mid-morning hours in the case of City-Windsor, the effect of sky cover is quite small. The wind speed has a similar influence during the night in winter, but has a comparatively smaller effect at night in summer. The influence of sky cover and the wind

Table 2. Coefficients by Multiple Regression Analysis

(a) City-Metro

January

Time Const.	0100	0400	0700	1000	1300	1600	1900	2200	All Day
A ₀	6.45	5.35	4.18	0.32	1.28	0.09	4.11	3.95	3.68
A ₁	0.03	-0.16	-0.20	-0.13	-0.17	0.01	-0.01	-0.12	-0.14
A ₂	-0.23	-0.20	-0.25	-0.04	-0.02	0.02	-0.04	-0.16	-0.12
A ₃	-0.01	0.03	0.04	0.02	0.04	0.00	-0.01	0.02	0.03
A ₄	-0.34	-0.27	0.03	0.23	-0.13	0.09	-0.20	-0.02	-0.10

July

Time Const.	0100	0400	0700	1000	1300	1600	1900	2200	All Day
A ₀	-20.5	-26.2	-11.9	-8.2	-8.2	-11.8	-17.7	-28.2	-6.7
A ₁	0.28	0.61	0.19	0.06	0.06	0.11	0.19	0.41	0.02
A ₂	0.06	-0.20	-0.11	0.24	0.15	0.03	0.21	0.07	0.04
A ₃	0.01	-0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.02
A ₄	-0.33	-0.21	-0.21	0.05	-0.24	0.04	0.01	-0.23	-0.23

Table 2. (cont'd)

(b) City-Windsor

January

Time Const.	0100	0400	0700	1000	1300	1600	1900	2200	All Day
A ₀	2.95	-0.56	0.44	0.07	1.10	0.45	-0.43	1.87	0.90
A ₁	0.10	-0.14	-0.26	-0.01	-0.09	-0.02	-0.12	-0.08	-0.07
A ₂	-0.06	0.03	-0.21	-0.01	-0.04	0.02	0.01	-0.14	-0.05
A ₃	-0.01	0.04	0.06	0.02	0.03	0.01	-0.04	0.02	0.02
A ₄	-0.19	0.01	0.23	-0.05	-0.06	-0.09	-0.11	0.03	-0.03

July

Time Const.	0100	0400	0700	1000	1300	1600	1900	2200	All Day
A ₀	-12.1	-22.6	-14.2	2.9	2.0	0.5	-8.8	-10.5	-7.8
A ₁	0.21	0.53	0.27	-0.01	-0.02	0.03	0.14	0.25	0.06
A ₂	0.05	0.06	0.05	0.01	0.06	-0.02	-0.02	-0.02	0.02
A ₃	0.00	-0.04	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00
A ₄	-0.02	0.01	0.03	-0.07	-0.15	-0.11	-0.15	-0.03	-0.09

speed agrees quite well with Sundborg's¹ study in Uppsala, Sweden and Chandler's⁷ study in London.

The actual temperature has either a negligible or a small decreasing effect on the difference during most hours in winter, but has an increasing effect in summer, especially during the late night and early morning hours. This is also in agreement with what Chandler found in London.

The coefficient of vapour pressure is generally small in winter and is still smaller in summer - almost zero during most hours. Thus the influence of vapour pressure on the temperature difference is negligible in winter and can be almost ignored in summer. It should be recalled here that Chandler, in his study of the temperature difference in London did not take vapour pressure into consideration because of its negligible influence.

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CHAPTER V

CONCLUSIONS

The urban heat island in the Detroit-Windsor area has been studied using three-hourly temperature observations at three airport stations in the area. Ten years of data were analyzed on an yearly and monthly basis and the seasonal and daily variation of the mean temperature difference has been studied. The significant conclusions are the following:

(1) The temperature difference has been found to be statistically significant during most hours of the day in the case of City-Windsor, and only during the night, early morning and late evening hours in the case of City-Metro. During the afternoon hours significance was found only in a few cases in the City-Metro difference.

(2) When the analysis was done using the average of the eight observations as one observation for the day, it was found that during certain seasons the significance of the difference was not brought out. It can therefore be said that, studies based on maximum, minimum or mean temperatures are inadequate for the investigation of seasonal or daily variations in the difference.

(3) The urban heat island was found to have a maximum in fall (summer maximum for City-Windsor) and a

minimum in winter. In Western Europe the maximum heat island intensities are noticed in summer, but in Japan the maximum is in winter. In Central and Northern Europe there seems to be no difference between summer and winter intensities. The mean difference of 1.5°F and 2.0°F in the two cases of city-country differences are of the same order of magnitude as found in other cities such as Paris and London.

(4) When the variation of the intensity of the urban heat island during the day was considered, the City-Metro difference was found to have a maximum late in the night with City-Windsor having a slightly higher value earlier in the night. The former intensity becomes almost zero late in the afternoon, while the reduction in the latter is relatively small and happens earlier during the day.

(5) As regards the multiple regression analysis it was found that cloudiness and wind speed have a decreasing effect on the temperature difference, especially during the night hours. The actual temperature has an increasing effect on the difference in summer, but a negligible effect in winter. The vapour pressure has very little effect on the temperature difference.

The present study analyzes the temporal variations of the urban heat island in detail. No attempt has been made to study the spatial pattern of the urban heat island of this area. There is a need for more research in this direction and also on the influence of radiation and pollution on the urban heat island.

APPENDIX A

Clapeyron-Clausius Formula

The Clapeyron-Clausius formula is

$$\log_{10} \frac{p_2}{p_1} = \frac{L_v}{4.576} \left(\frac{T_2 - T_1}{T_1 T_2} \right)$$

where p_1 and p_2 are pressures at absolute temperatures T_1 and T_2 respectively and L_v is the latent heat of vaporization in calories per mole and is equal to 18 times 542 for water vapour. If T_1 is taken as the boiling point of water under normal atmospheric pressure, then,

$$T_1 = 212 + 459.7 = 671.7^\circ \text{Abs.}$$

$$p_1 = 29.92 \text{ inches of mercury.}$$

The saturated vapour pressure p_2 at any temperature T_2 can be calculated using the above formula. The actual vapour pressure at this temperature may be obtained by multiplying the saturated vapour pressure by the relative humidity.

APPENDIX B

SIGNIFICANCE-TESTING PROGRAM

THIS PROGRAM READS THE 3-HOURLY TEMPERATURE DATA FOR THE CITY, METRO AND WINDSOR AIRPORT STATIONS, CALCULATES AND PRINTS THE CITY-METRO, CITY-WINDSOR AND METRO-WINDSOR DIFFERENCES BETWEEN CORRESPONDING TEMPERATURES, CALCULATES THE MEAN DIFFERENCE AND STANDARD ERROR OF DIFFERENCE AND TESTS FOR SIGNIFICANCE USING THE T-TEST. IT ALSO CALCULATES THE 99% CONFIDENCE LIMITS FOR THE MEAN DIFFERENCE. THE ABOVE CALCULATIONS ARE DONE FOR THE WHOLE YEAR AND FOR EACH MONTH FIRST WITH ALL THE 8 OBSERVATIONS TAKEN TOGETHER AND THEN FOR EACH OBSERVATION HOUR.

```

DIMENSION MH(370),ID(370),IC(12,32,8),IM(12,32,8),IW(12,32,8)
DIMENSION NM(12),D(3,366,8), T2(3),T1(3),SH(8),SQH(8)
DIMENSION A(39),      AT(6),AH(6,8) ,SI(8)
READ 405,ANO,YES
READ 105,(A(I),I=1,39)
105 FORMAT (20A4)
DO 200 K=1,3
N=0
I=1
NM(1)=0
110 N=N+1
NM(I)=NM(I)+1
IF (K-2) 120,130,140
120 READ 150,IR,MH(N),ID(N),((IC(MH(N),ID(N),J),J=1,8)
GO TO 160
130 READ 150,IR,MH(N),ID(N),((IM(MH(N),ID(N),J),J=1,8)
GO TO 160
140 READ 150,IR,MH(N),ID(N),((IW(MH(N),ID(N),J),J=1,8)
150 FORMAT (2X,3I2,12X,8I5)
160 IF (MH(N)-1) 180,110,170
170 IF (ID(N)-31) 180,180,175
175 N=N-1
NM(I)=NM(I)-1
GO TO 200
180 IF (ID(N)-1) 200,190,110
190 NM(I)=NM(I)-1
I=I+1
NM(I)=1
GO TO 110
200 CONTINUE
DO 210 I=1,N
K=MH(I)
L=ID(I)

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      DO 210 J=1,8
      D(1,I,J)=IC(K,L,J)-IM(K,L,J)
      D(2,I,J)=IC(K,L,J)-IW(K,L,J)
      D(3,I,J)=IM(K,L,J)-IW(K,L,J)
210  CONTINUE
      KT=0
230  PRINT 240
240  FORMAT (111H1
1     AIRPORT
      CITY-MET
      DET CITY
      CITY-WIN
      DET METRO
      MET-WIN )
      DO 270 I=1,6
      KT=KT+1
      K=MH(KT)
      L=ID(KT)
      PRINT 250,IR,K,L
250  FORMAT (1H0,3I4)
      PRINT 260,((IC(K,L,J),IM(K,L,J),IW(K,L,J),D(1,KT,J),D(2,KT,J),
1     D(3,KT,J)),J=1,8)
260  FORMAT (12X,3I15,13X,3F13.1)
      IF (KT-N) 270,280,280
270  CONTINUE
      GO TO 230
280  CONTINUE
      PRINT 285,N
285  FORMAT (/25H0TOTAL NO OF DATA DAYS = ,I4)
      PRINT 290,IR
290  FORMAT (49H1
1H0
      RESULTS FOR THE YEAR 19,I2/64
      ANALYSIS FOR THE WHOLE YEAR )
      T1(1)=2.33
      T1(2)=2.33
      T1(3)=2.33
      T2(1)=2.33
      T2(2)=2.33
      T2(3)=2.33
      K1=1
      K2=12
      C1=2.576
      C2=2.576
      MT1=1
      DO 540 KT=1,13
      M1=0
      DO 300 K=K1,K2
      NMK=NM(K)
      DO 300 L=1,NMK
      M1=M1+1
300  CONTINUE
      MT2=MT1+M1-1
      DO 490 I=1,3
      ST=0.0
      SQT=0.0
      DO 310 J=1,8
      SH(J)=0.0

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      SQH(J)=0.0
      DO 310 M=MT1,MT2
      ST=ST+D(I,M,J)
      SQT=SQT+D(I,M,J)**2
      SH(J)=SH(J)+D(I,M,J)
      SQH(J)=SQH(J)+D(I,M,J)**2
310  CONTINUE
      AM=M1
      AT(1)=ST/(M1*8)
      AT(2)=SQRT((SQT-ST**2/(M1*8))/(M1*8-1))
      AT(3)=AT(2)/SQRT(AM*8.)
      AT(4)=AT(1)+C1*AT(3)
      AT(5)=AT(1)-C1*AT(3)
      AT(6)=AT(1)/AT(3)
      DO 320 J=1,8
      AH(1,J)=SH(J)/M1
      AH(2,J)=SQRT((SQH(J)-SH(J)**2/M1)/(M1-1))
      AH(3,J)=AH(2,J)/SQRT(AM)
      AH(4,J)=AH(1,J)+C2*AH(3,J)
      AH(5,J)=AH(1,J)-C2*AH(3,J)
      AH(6,J)=AH(1,J)/AH(3,J)
320  CONTINUE
      IF (I-2) 330,340,350
330  PRINT 360
      GO TO 390
340  PRINT 370
      GO TO 390
350  PRINT 380
360  FORMAT(/27HDETROIT CITY-DETROIT METRO )
370  FORMAT(/29HDETROIT CITY-WINDSOR AIRPORT )
380  FORMAT(/30HDETROIT METRO-WINDSOR AIRPORT )
390  PRINT 400
400  FORMAT (105H0                      MEAN DIFF    S.D.OF DIFF  ST. ERROR
1     99% CONFID. LIMITS                T      SIGNIFICANT?    )
405  FORMAT (2A3)
      IF (AT(6)-T1(I)) 410,410,420
410  SIG=AND
      GO TO 430
420  SIG=YES
430  PRINT 440,(AT(M),M=1,6),SIG
440  FORMAT (13HWHOLE PERIOD, F11.3,5F13.3,7X,A3)
      DO 490 J=1,8
      JH=3*J-2
      IF (AH(6,J)-T2(I)) 450,450,460
450  SI(J)=AND
      GO TO 470
460  SI(J)=YES
470  PRINT 480,JH,(AH(M,J),M=1,6),SI(J)
480  FORMAT (5H0HOUR,I3,3X,6F13.3,7X,A3)
490  CONTINUE
      PRINT 495

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495 FORMAT (105H0.....)
1.....)
  MT1=MT1+M1
  IF (KT-1) 500,500,520
500 PRINT 510
510 FORMAT (///50H0          MONTH BY MONTH ANALYSIS )
  MT1=1
  T2(1)=2.47
  T2(2)=2.47
  T2(3)=2.47
  C2=2.76
520 K1=KT
  K2=KT
  PRINT 530,A(3*KT-2),A(3*KT-1),A(3*KT)
530 FORMAT (//50X,3A4)
540 CONTINUE
  STOP
  END
```

APPENDIX C

MULTIPLE REGRESSION ANALYSIS PROGRAM

THIS PROGRAM CALCULATES BY MULTIPLE REGRESSION ANALYSIS, THE REGRESSION CONSTANT AND THE COEFFICIENTS OF THE INDEPENDENT VARIABLES. IT ALSO CALCULATES THE MULTIPLE CORRELATION COEFFICIENT AND THE PARTIAL CORRELATION COEFFICIENTS.

```

DIMENSION X(250,10),D(10,10),A(25),E(10,10),EX(20)
DIMENSION LX(10),MX(10),LY(10),MY(10)
DIMENSION K1(4,31,8),K2(4,31,8),X1(4,31,8),X2(4,31,8)
DIMENSION B(10),SUM(10),SB(10),RYX(10),T(10)
READ 1,N,M1
1 FORMAT (I2,I3)
READ 2,(((K1(I,J,K),K=1,8),J=1,M1)
READ 2,(((K2(I,J,K),K=1,8),J=1,M1)
2 FORMAT (20X,8I5)
READ 3,(((K1(I,J,K),I=2,4),K=1,8),J=1,M1)
READ 3,(((K2(I,J,K),I=2,4),K=1,8),J=1,M1)
3 FORMAT (8X,24I3)
PRINT 4,(((K1(I,J,K),I=1,4),K=1,8),J=1,M1)
PRINT 4,(((K2(I,J,K),I=1,4),K=1,8),J=1,M1)
4 FORMAT (33H1DATA-TEMP.,W.SPEED,R.H,SKY COVER / (1H0,32I4))
N1=N+1
N2=N-1
KI=1
KF=8
DO 45 I=1,4
DO 45 J=1,M1
DO 45 K=1,8
X1(I,J,K)=K1(I,J,K)
45 X2(I,J,K)=K2(I,J,K)
PRINT 46
46 FORMAT (27H1CALCULATIONS FOR ALL HOURS )
DO 22 IJ=1,9
M=0
DO 6 K=KI,KF
DO 6 J=1,M1
M=M+1
X1(2,J,K)=1.1516*K1(2,J,K)
P1=542.0*18.0/4.576*(K1(1,J,K)-212.0)/671.7/(K1(1,J,K)+459.7)
P2=542.0*18.0/4.576*(K2(1,J,K)-212.0)/671.7/(K2(1,J,K)+459.7)
X1(3,J,K)=K1(3,J,K)*29.921*10.0**P1
X2(3,J,K)=K2(3,J,K)*29.921*10.0**P2
DO 5 I=1,N2
5 X(M,I+1)=(X1(I,J,K)+X2(I,J,K))/2.0

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      X(M,1)=1.0
6     X(M,N1)=X1(1,J,K)-X2(1,J,K)
      DO 10 K=1,N
      DO 10 J=1,N1
      D(K,J)=0.0
      DO 10 I=1,M
10    D(K,J)=D(K,J)+X(I,J)*X(I,K)
      DO 11 I=1,N
      B(I)=D(I,N1)
      DO 11 J=1,N
      II=(J-1)*N+I
11    A(II)=D(I,J)
      DO 12 J=1,N1
12    D(1,J)=D(1,J)/M
      NN=N*N
      PRINT 13,(A(II),II=1,NN)
13    FORMAT (7HOMATRIX/(1H0,5F16.8))
      PRINT 13,(B(I),I=1,N)
      DO 145 J=2,N1
      SUM(J)=0.0
      DO 14 I=1,M
14    SUM(J)=SUM(J)+(X(I,J)-D(1,J))*(X(I,N1)-D(1,N1))
145   CONTINUE
      CALL SIMQ(A,B,N,KS)
      PRINT 146,(B(I),I=1,N)
146   FORMAT (20HOCOEFFICIENTS.....,5F16.8)
      F=0.0
      SYSQ=SUM(N1)
      DO 147 I=2,N
      SYSQ=SYSQ-B(I)*SUM(I)
147   F=B(I)*SUM(I)+F
      SYSQ=SYSQ/(M-N)
      RSQ=F
      F=F/(N2*SYSQ)
      PRINT 15,F
15    FORMAT (3HOF=,F16.8)
      RSQ=RSQ/SUM(N1)
      R=SQRT(RSQ)
      PRINT 155,R
155   FORMAT (3HCR=,F10.8)
      DO 16 K=2,N
      DO 16 J=2,N1
      E(K-1,J-1)=0.0
      DO 16 I=1,M
16    E(K-1,J-1)=E(K-1,J-1)+(X(I,J)-D(1,J))*(X(I,K)-D(1,K))
      DO 17 I=1,N2
      DO 17 J=1,N2
      II=(J-1)*N2+I
17    EX(II)=E(I,J)
      CALL MINV(EX,N2,DET,LY,MY)
      DO 18 I=1,N2

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      II=(I-1)*N2+I
      RYX(I)=E(I,N)/(SQRT(E(I,I)*SUM(N1)))
      SB(I)=SQRT(SYSQ*EX(II))
18    T(I)=B(I+1)/SB(I)
      PRINT 19,(SB(I),I=1,N2),(T(I),I=1,N2)
19    FORMAT (4H0SB=,4F16.8,6H      T= ,4F14.4)
      PRINT 21,(RYX(I),I=1,N2)
21    FORMAT (4HORY=,4F16.8)
      KI=IJ
      KF=IJ
      IH=3*IJ-2
      IF (IJ-9) 214,22,22
214  PRINT 215,IH
215  FORMAT (/////21HOCALCULATION FOR HCUR ,I3)
22  CONTINUE
      STOP
      END
```

APPENDIX D

Mean Differences

1960-69.

(a) City-Metro

Time	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
0100	1.50	1.65	2.60	3.84	4.04	2.09	2.44	2.53	2.79	1.67
0400	1.61	1.81	2.40	3.78	3.88	2.02	2.42	2.45	2.74	1.57
0700	1.43	1.63	2.09	3.33	3.59	1.64	2.09	2.56	2.92	1.75
1000	0.07	0.66	0.59	1.39	1.99	0.24	0.54	0.96	1.06	0.01
1300	-0.49	-0.22	0.20	0.81	1.29	-0.23	0.12	0.14	0.37	-0.55
1600	-0.41	-0.11	0.10	0.41	1.08	-0.27	-0.15	0.24	0.22	-0.77
1900	0.46	0.72	1.85	2.20	2.59	1.15	1.23	1.50	1.63	0.44
2200	1.20	1.44	2.88	3.67	3.76	1.91	2.33	2.67	2.84	1.68
All Day	0.67	0.95	1.59	2.43	2.78	1.07	1.38	1.63	1.82	0.73

(b) City-Windsor

Time	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
0100	1.49	1.90	1.70	2.53	2.82	2.64	2.42	2.62	3.54	1.59
0400	1.20	1.61	1.26	2.26	2.42	2.39	2.28	2.48	3.46	1.12
0700	0.91	1.57	0.99	2.27	2.23	1.96	1.90	2.39	3.27	1.24
1000	0.24	0.94	0.63	1.56	1.74	1.45	1.58	1.96	2.85	1.15
1300	0.74	1.28	1.13	1.91	2.00	1.70	1.79	1.89	2.81	1.52
1600	0.91	1.18	0.98	1.73	1.90	1.67	1.77	1.94	2.78	1.19
1900	1.37	1.81	1.66	2.29	2.45	2.35	2.61	2.58	3.48	1.57
2200	1.89	2.32	2.28	3.06	2.94	2.78	2.97	3.11	4.10	1.90
All Day	1.09	1.58	1.53	2.20	2.31	2.12	2.16	2.37	3.29	1.41

(c) Metro-Windsor

Time	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
0100	-0.01	0.25	-0.90	-1.31	-1.22	0.55	-0.02	0.09	0.76	-0.08
0400	-0.40	-0.20	-1.13	-1.52	-1.46	0.37	-0.15	0.04	0.72	-0.45
0700	-0.53	-0.06	-1.09	-1.06	-1.36	0.33	-0.19	-0.18	0.35	-0.51
1000	0.17	0.28	0.04	0.17	-0.25	1.21	1.04	1.00	1.80	1.14
1300	1.23	1.50	0.92	1.10	0.71	1.92	1.67	1.74	2.44	2.07
1600	1.32	1.30	0.88	1.32	0.82	1.93	1.92	1.70	2.56	1.96
1900	0.92	1.09	-0.19	0.09	-0.14	1.20	1.38	1.03	1.84	1.13
2200	0.69	0.88	-0.60	-0.61	-0.81	0.87	0.64	0.44	1.26	0.23
All Day	0.42	0.63	-0.26	-0.23	-0.46	1.05	0.79	0.74	1.47	0.68

APPENDIX E

Average of Mean Differences

(a) City-Metro

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day
Year	2.51	2.47	2.30	0.75	0.15	0.03	1.38	2.44	1.50
Jan.	1.46	1.53	1.62	0.82	0.07	0.04	1.12	1.50	1.02
Feb.	1.18	1.15	1.15	0.01	-0.39	-0.52	0.64	1.11	0.54
Mar.	1.55	1.42	1.53	0.26	-0.05	-0.20	0.84	1.22	0.82
Apr.	2.06	1.98	1.96	0.15	-0.04	0.16	0.91	1.20	1.15
May	2.43	2.51	1.99	0.45	0.20	0.25	1.09	2.49	1.43
June	2.98	3.05	2.53	0.67	0.15	-0.22	0.93	2.95	1.61
July	3.35	3.02	2.45	0.67	0.21	0.12	0.81	3.14	1.72
Aug.	3.49	3.57	3.25	1.19	0.48	0.07	1.54	3.51	2.14
Sep.	3.51	3.31	3.16	1.06	0.34	0.23	2.40	3.41	2.18
Oct.	3.93	3.83	3.75	1.31	0.28	0.07	2.79	3.62	2.45
Nov.	2.50	2.43	2.60	1.25	0.30	0.24	2.02	2.43	1.72
Dec.	1.67	1.68	1.77	1.12	0.16	0.12	1.40	1.80	1.22

(b) City-Windsor

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day
Year	2.33	2.05	1.87	1.41	1.68	1.60	2.22	2.74	1.99
Jan.	1.58	1.71	1.68	1.06	1.15	1.20	1.58	1.83	1.47
Feb.	1.45	1.42	1.23	0.76	1.34	1.26	1.57	1.78	1.35
Mar.	2.08	1.91	1.74	1.46	1.83	1.70	2.20	2.20	1.89
Apr.	2.69	2.23	2.02	1.30	1.73	1.70	2.25	3.09	2.12
May	2.65	2.42	1.86	1.52	1.82	1.81	2.25	3.22	2.20
June	2.65	2.26	2.16	1.82	1.83	1.73	2.25	3.40	2.26
July	2.73	2.17	1.82	1.67	1.72	1.64	1.86	3.32	2.12
Aug.	2.76	2.36	2.16	1.92	2.20	1.88	2.54	3.50	2.42
Sep.	2.55	2.20	1.95	1.73	2.02	1.87	2.86	3.05	2.28
Oct.	2.87	2.35	2.46	1.37	1.78	1.59	3.02	3.18	2.33
Nov.	2.11	1.88	1.85	1.24	1.44	1.55	2.40	2.34	1.85
Dec.	1.74	1.60	1.51	1.04	1.24	1.30	1.80	1.86	1.51

(c) Metro-Windsor

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day
Year	-0.19	-0.42	-0.43	0.66	1.53	1.57	0.84	0.30	0.48
Jan.	0.12	0.17	0.06	0.23	1.09	1.61	0.47	0.33	0.45
Feb.	0.27	0.27	0.08	0.76	1.73	1.78	0.93	0.68	0.81
Mar.	0.53	0.49	0.21	1.21	1.88	1.90	1.36	0.98	1.07
Apr.	0.64	0.25	0.06	1.14	1.77	1.53	1.33	1.09	0.98
May	0.22	-0.09	-0.13	1.07	1.62	1.56	1.17	0.73	0.77

(c) Metro-Windsor (cont'd)

Time Period	0100	0400	0700	1000	1300	1600	1900	2200	All Day
June	-0.33	-0.79	-0.16	1.15	1.67	1.95	1.32	0.45	0.66
July	-0.62	-0.85	-0.63	1.00	1.51	1.52	1.06	0.18	0.40
Aug.	-0.73	-1.21	-1.08	0.73	1.72	1.81	1.00	0.00	0.28
Sep.	-0.96	-1.11	-1.20	0.66	1.68	1.64	0.47	-0.36	0.10
Oct.	-1.06	-1.48	-1.29	0.06	1.49	1.53	0.23	-0.44	-0.12
Nov.	-0.39	-0.55	-0.76	0.00	1.15	1.31	0.37	-0.09	0.13
Dec.	0.07	-0.08	-0.26	-0.09	1.08	1.18	0.39	0.06	0.30

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